Drowned landscapes of the eastern English Channel: records of Quaternary environmental change

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by

Claire Louise Mellett

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Abstract

The present-day seabed in the eastern English Channel is an erosional landscape dissected by a complicated network of palaeovalleys. The largest of these palaeovalleys has been interpreted as the product of catastrophic flooding though the Straits of Dover during the Mid Quaternary. Whilst the eastern English Channel is a valuable source of aggregates, little attention has been paid to the sedimentary record preserved on the continental shelf in terms of its ability to document landscape change throughout the Quaternary. This thesis aims to establish the first stratigraphic model of deposits preserved on the continental shelf in the eastern English Channel and chronometrically constrain the timing of deposition using Optical Stimulated Luminescence (OSL) dating. The model will be used as a framework to reconstruct landscape change and address questions regarding the preservation potential of sediments, and the imprint sedimentary processes have on the landscape, in continental shelf settings over glacial-interglacial cycles. The stratigraphic model was constructed through the integration of high resolution mutlibeam bathymetry, shallow sub-surface 2D seismic profiles, lithological information from vibrocores, and chronometric data obtained through OSL. A variety of drowned landscapes including terrestrial (fluvial and colluvial), coastal and shallow marine, were identified. These landscapes document palaeoenvironmental change on the continental shelf from MIS 6 to MIS 1. The fluvial landscape in the English Channel is dominated by multiple phases of lateral and vertical erosion, primarily in response to changes in sea level, but also as a result of reorganisation of drainage basins and variable discharges due to fluctuating ice margins. Exposure of the continental shelf during cold periods is documented in the form of remnant periglacial deposits and extensive palaeosols. The most volumetrically significant sediments preserved on the continental shelf were deposited in shallow marine and coastal settings. These sediments are typically restricted to palaeovalleys where accommodation created during relative sea-level rise enabled deposition. Elsewhere, sediments are preserved as relict coastal landforms, in particular, as part of an exceptionally rare drowned barrier complex at Hastings Bank. Over multiple sea-level cycles, sediments are recycled by fluvial and marine processes, with the most recent phase of deposition having the greatest preservation potential. Erosional processes have the greatest persistence in the landscape record. However, they create a composite record and distinguishing between different events without a correlative sediment package is problematic. The results presented in this thesis highlight the timing and nature of 'normal' sedimentary regimes in a continental shelf setting over multiple glacial-interglacial cycles. Further, they reveal evidence for erosion and deposition by fluvial processes in the Northern Palaeovalley during the last glacial period, thus contradicting an existing hypothesis that states the palaeovalley formed through catastrophic flooding.

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Firstly I would like to thank my primary supervisor, Andreas Lang, and my CASE supervisor, Ian Selby, for seeing the potential in using commercially acquired data to explore Quaternary evolution of the English Channel, and setting up the research project that forms this PhD. Throughout the project I have been lucky enough to have the support of five supervisors and have greatly benefited from their collective knowledge and experience across a range of disciplines.

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“Absence of evidence is not evidence of absence”

Carl Sagan

Contents

Chapter 1

Introduction

1.1 BACKGROUND

In mid-latitude settings that have been conditioned by glaciation and deglaciation i.e paraglacial (Ballantyne, 2002), the terrestrial stratigraphic record of the Quaternary is highly fragmented, as ice sheet advance over repeated cold stages destroyed and reworked sediments and landforms from preceding stages (Clark et al., 1978). Our understanding of Quaternary environmental change is therefore limited by the sedimentary record preserved and many questions remain unanswered. Terrestrial and deep marine sediment archives are commonly used in Quaternary science as records of environmental change (e.g. Shackleton and Opdyke, 1973; Penkman et al., 2012). However, in comparison continental shelves have received less attention in published literature. As part of the continuum between terrestrial and deep marine settings, continental shelves are a vital link in basin studies (e.g. Catuneanu, 2006) and have the potential to fill gaps in the fragmentary stratigraphic record (e.g. Suter and Berryhill, 1985). This requires an understanding of the timing and nature of processes operating on the continental shelf, and the preservation potential of the record they leave behind.

The sediments and landforms preserved on the eastern English Channel continental shelf are potential archives of Quaternary environmental change. The Quaternary history of northwest Europe has been strongly conditioned by the presence or absence of a land bridge at the Straits of Dover (see Preece, 1995; Gibbard and Lautridou, 2003 for an introduction). The timing and mechanism of breaching at the Straits of Dover is currently under debate (Smith, 1985; Gibbard et al., 1988; Gupta et al., 2007; Busschers et al., 2008; Westaway and Bridgland, 2010). Bedrock morphology of the eastern English Channel has been interpreted as the product of catastrophic flooding when the land bridge at the Straits of Dover was initially breached (Gupta et al., 2007). This interpretation is based on analysis of bathymetric data only and does not consider the sedimentary record preserved in the subsurface. Further, it is limited by a lack of chronometric data to constrain the timing of postulated flood event/s. The eastern English Channel continental shelf as a conduit for discharge through the Straits of Dover can be utilised to test competing hypotheses and further improve our understanding of Quaternary history in northwest Europe.

1.2 THESIS AIMS

The principal objective of this thesis is to establish the first stratigraphic model of Quaternary deposits preserved on the eastern English Channel continental shelf by integrating marine geophysics and core data. This model will provide a framework to constrain the relative timing and nature of processes driving erosion and deposition on the continental shelf during the Quaternary. In an attempt to chronometrically constrain the model, the application of Optical Stimulated Luminescence (OSL) dating to deposits preserved on the continental shelf, will be tested. Finally, the model will be used to reconstruct landscape change in the eastern English Channel and address questions regarding the preservation potential of sediments in a shelf environment. With this in mind, the research presented in this thesis is framed around the following key scientific questions.

Question 1: *What landscapes and sediments are preserved on the eastern English Channel continental shelf and what are the sequence, timing and nature of processes that led to their development?*

Rationale: Significant thicknesses (up to 30 m) of coarse clastic sediments are preserved on the continental shelf in the eastern English Channel (Hamblin et al., 1992). These deposits are important aggregate resources (BMAPA and The Crown Estate, 2007). However, little is known about their origin (source area and transport history) and development (sedimentary processes and environments of deposition). Further, the erosional morphology of the seabed has long been recognised as a remnant of terrestrial landscapes that existed during periods of lowered sea-level (Dingwall, 1975; Smith, 1985; Gibbard et al., 1988; Bellamy, 1995; Antoine et al., 2003; Gupta et al., 2007). These landscapes can be explored further by calibrating geophysical and core data acquired as part of aggregate prospecting schemes operating in the eastern English Channel. These drowned landscapes offer an opportunity to address questions regarding the sequence, timing and nature of processes operating on the continental shelf at the glacial- interglacial timescale. This case study can be used to test widely-applied models of continental shelf stratigraphy (see Suter, 2006 for a review) preserved in ancient sedimentary basins.

Question 2: *What is the preservation potential of landscapes on the continental shelf over the Quaternary period?*

Rationale: The preservation potential of landforms and sediments over high frequency, high magnitude sea-level changes characteristic of the Quaternary is an important consideration when using continental shelf records as archives of palaeoenvironmental change. Over longer geological timescales an inherent bias towards the preservation of depositional processes is incorporated into the stratigraphic record and information about the processes driving erosion and non-deposition is difficult to extract (Reading, 1996). In continental shelf settings over glacial-interglacial timescales, repeated sea-level fluctuations drive dramatic landscape change from terrestrial to fully marine (e.g. Catuneanu et al., 2009). Preserved on the seabed in the eastern English Channel is the morphological expression of a complex network of palaeovalleys that are locally filled with sedimentary deposits (Hamblin et al., 1992). Therefore, the preservation potential of erosional processes at the Quaternary timescale is high. However, little is known about the conditions and processes required to preserve such landscapes on a transgressive continental shelf and their persistence in the geological record.

Question 3: *What is the relative significance of 'catastrophic' and 'normal' processes in shaping palaeovalleys in the eastern English Channel?*

Rationale: The separation of Britain as an island from continental Europe is a significant event in the Quaternary history of northwest Europe with debates regarding the timing and mechanism of this event still unresolved. Two principal mechanisms have been proposed to explain breaching at the Straits of Dover and subsequent isolation of Britain; (i) gradual degradation of a bedrock-dominated landscape over several sea level cycles as a result of fluvial down-cutting (Dingwall, 1975; Gibbard et al., 1988; Busschers et al., 2008; Westaway and Bridgland, 2010), i.e. 'normal' processes driven by background sedimentary regimes, and; (ii) high magnitude, low frequency 'catastrophic' processes driven by event scale 'megaflooding' and carving of the bedrock from draining of a proglacial lake impounded in the southern North Sea (Smith, 1985; Gibbard, 2007; Gupta et al., 2007). Formation of the Northern Palaeovalley in the eastern English Channel has been linked to the processes responsible for initial breaching at the Straits of Dover (Gupta et al., 2007). Therefore, the close proximity of the eastern English Channel to the Straits of Dover, and the dramatic erosional morphology of the present-day seabed make the stratigraphic record preserved in the eastern English Channel a vital resource for testing the two conflicting hypotheses.

Question 4: *Are sediments preserved on continental shelves suitable for Optical Stimulated Luminescence dating?*

Rationale: Reliable reconstructions of Quaternary environmental change require a robust chronology. Optical Stimulated Luminescence (OSL) dating is used to determine the time of sediment deposition by dating the time elapsed since silt or sand size grains of quartz or feldspar were exposed to light. It has been proved successful across a range of depositional settings encompassing aeolian (e.g. Wintle, 1993), fluvial (e.g. Wallinga, 2002), coastal and marine (e.g. Jacobs, 2008), periglacial (e.g. Bateman, 2008) and glaciofluvial (e.g. Thrasher et al., 2009a) systems. There are few examples that demonstrate the application of OSL to sediments preserved on submerged continental shelves (Gupta et al., 2004; Alappat et al., 2010; Guedes et al., 2011). Theoretically, if sediments preserved on the continental shelf were deposited in terrestrial and/or shallow marine settings during periods of lower sea-level, establishing a chronology using OSL should follow standard procedures (e.g Mauz et al., 2010). However, poor understanding of continental shelf stratigraphy and the processes that permit preservation of drowned landscapes, has thus far limited the application of the technique in this context. An investigation into the suitability of OSL in dating a range of drowned landscapes preserved on the continental shelf, where the stratigraphy is well constrained, is therefore required.

1.3 THESIS LAYOUT

This thesis comprises three manuscripts that have been accepted, or submitted, for publication in international peer-reviewed journals (Chapter 4 to 6). Each of the chapters addresses different research questions as summarised in Fig. 1.1.

Chapter 2: *Quaternary history of the English Channel.* Provides a brief introduction into present understanding of Quaternary history of the English Channel. This is followed by a review of ongoing debates about the timing and nature of breaching at the Straits of Dover, that led to the isolation of Britain as an island during periods of high sea level stand.

Chapter 3: *Integrating marine geophysics and core data.* Presents an overview of shallow marine geophysics and coring techniques and presents the methodological approach to data integration employed in this thesis.

Chapter 4: *Preservation of a drowned gravel barrier complex: a landscape evolution study from the north-eastern English Channel* – published in Marine Geology: this chapter presents a high resolution stratigraphic model of a previously undocumented, yet exceptionally well preserved, drowned barrier complex. The stratigraphic model is used as a framework to reconstruct evolution of a shoreline under rapid rates of early Holocene sea-level rise. This chapter evaluates the conditions and processes responsible for barrier initiation, breakdown and retreat and examines under what scenarios barrier deposits are preserved seaward of advancing shorelines.

Chapter 5: *Optical dating of drowned landscapes: a case study from the English Channel* – published in Quaternary Geochronology: This chapter tests the application of OSL to a variety of drowned landscapes preserved in the eastern English Channel. Methodological considerations relating to; (i) quartz provenance on continental shelves; (ii) changes in water content over repeated sea-level cycles, and (iii) attenuation of cosmic dose rate in drowned landscapes, are discussed.

Chapter 6: *Landscape degradation of the continental shelf between Britain and France at the glacial-interglacial timescale* – submitted to Geomorphology: this chapter integrates the data presented in Chapters 4 and 5 within a regional stratigraphic context. It presents the first detailed chronometrically constrained record of erosional and depositional events in the eastern English Channel. Palaeogeographic evolution of the English Channel through the Mid- to Late Quaternary is reconstructed. The timing and nature of processes operating on paraglacial continental shelves, and the preservation potential of drowned landscapes, over glacial-interglacial timescales, is assessed.

Chapter 7: is an extended discussion that addresses the key scientific questions outlined in Chapter 1 by synthesising the findings from research carried out in chapters 4 to 6. This chapter also includes conclusions, considers the wider implications of this research and addresses future priorities in this field.

1.4 AUTHOR CONTRIBUTION AND STATUS OF MANUSCRIPTS

This thesis comprises three core chapters intended for publication in international peer reviewed journals. At the time of thesis submission the status of these manuscripts is as follows;

Chapter 4: Mellett, C. L., Hodgson, D. M., Lang, A., Mauz, B., Selby, I. and Plater, A. J. (2012). Preservation of a drowned gravel barrier complex: a landscape evolution study from the north-eastern English Channel. Marine Geology, 315-318, 115-131.

Author contribution: Mellett, C. L. – Main author. Responsible for data collection, processing, collation and interpretation, and for writing the manuscript.

Hodgson, D. M. – In depth discussions and detailed manuscript review.

Mauz, B. – Discussions and manuscript review.

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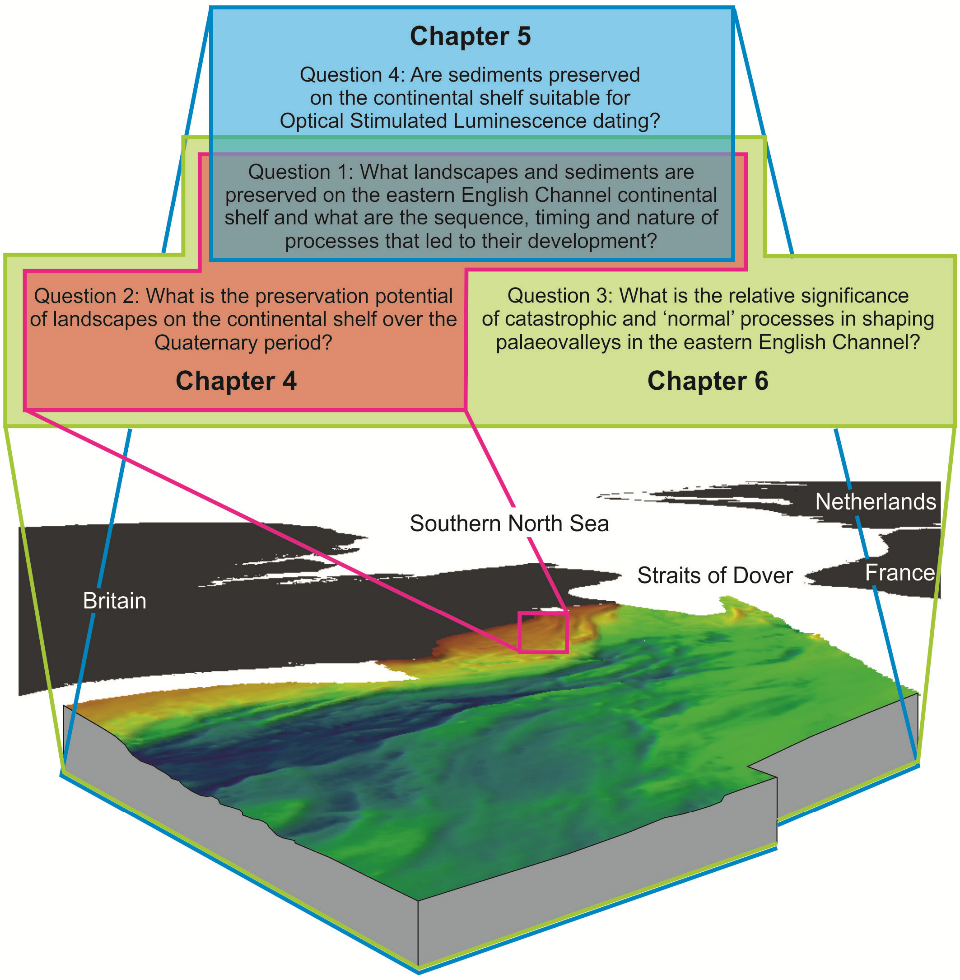

Figure 1.1: Eastern English Channel study site highlighting the area represented by each chapter and the key research questions posed.

Chapter 5: Mellett, C. L., Mauz, B., Plater, A. J., Hodgson, D. M. and Lang, A. (2012) Optical dating of drowned landscapes: a case study from the English Channel. Quaternary Geochronology, 10, 201-208.

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Mauz, B. – Assistance with data analysis, in depth discussions and detailed manuscript review.
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Chapter 2

Quaternary history of the English Channel

2.1 BACKGROUND

Throughout the Quaternary the English Channel continental shelf has been conditioned by glaciation and deglaciation. However, based on the current understanding of ice margins (Elhers et al., 2011) there is no evidence to suggest it has been overlain by ice, and can be therefore characterised as a paraglacial system according to Ballantyne (2002). Structurally, the English Channel has experienced continuous uplift throughout the Quaternary whilst neighbouring areas, such as the North Sea and Western Approaches, have been subsiding (Van Vliet-Lanoe et al., 2000). Present-day water depths in the English Channel are typically <100 m making it a shallow seaway. Therefore, in response to high magnitude, high frequency, changes in relative sea-level, a characteristic of the Quaternary, the continental shelf has been repeatedly exposed and submerged, becoming variably susceptible to sedimentary processes operating in terrestrial, marine and transitional environments. The topography of the seabed as preserved today is interpreted as a relict terrestrial landscape that formed through fluvial incision under a periglacial climate (Dingwall, 1975; Gibbard et al., 1988; Lercolais, 1997; Bellamy, 1995; Antoine et al., 2003; Bates et al., 2003). This is not surprising considering the long duration of glacial stages, and thus periods of lower sea-level, relative to interglacial stages (Lisiecki and Raymo, 2005). Despite this, there is a record of sea-level highstand preserved in the English Channel in the form of submerged cliff-lines (Hamblin et al., 1992) and relict coastal deposits (Hails, 1975).

2.2 ISOLATION OF BRITAIN THROUGH BREACHING AT THE STRAITS OF DOVER

One of the most significant events in the Middle to Late Quaternary history of north-west Europe was the isolation of Britain as an island from the continental landmass (see Preece, 1995 for a review). Such major palaeogeographic reorganisation influenced the migration of flora and fauna, including hominins, across north-west Europe between glacial-interglacial sea-level cycles (Preece, 1995; Stringer, 2006; Hijma et al., 2012). During the Early Quaternary, Britain was connected to the European continental landmass, even during highstand via an extensive delta in the southern North Sea and the Weald-Artois anticline at the Straits of Dover (Funnell, 1995). This land bridge was breached at some point during the Mid-Quaternary through erosion of bedrock at the Straits of Dover, and Britain became an island, initially during lowstand periods and then during subsequent highstands as well (Gibbard, 1995).

The timing of initial breach has been closely linked to glacial maxima when sea-level was at lowstand and ice margins were at their maximum limits (Gibbard et al., 1988). Commonly a marine oxygen isotope stage (MIS) 12 age is proposed, as this stage saw the first major extension and coalescence of the British and Fennoscandian Ice Sheets (Elhers and Gibbard, 2004) that restricted drainage into the Atlantic Ocean via a northerly route. In response to this ice sheet advance, the river Thames adopted a more southerly route and flowed towards the Straits of Dover (Bridgland and D'Olier, 1995). There is sedimentary evidence to support the existence of an extensive lake in the southern North Sea basin at this time (Murton and Murton, 2012). It is proposed that the existence of the lake was maintained by discharge from the Thames and Rhine fluvial systems along with meltwater from proximal ice sheets. Lake out-flow to the south was restricted by the topography at the Straits of Dover, until a threshold was reached and the land bridge was breached (Gibbard et al., 1988; Gibbard, 1995). An increase in terriginous sediment input to the continental shelf margin during MIS 12, from capture of the Thames-Rhine fluvial systems due to breaching at the Straits of Dover (Toucanne et al., 2009a), supports a MIS 12 age for initial breach. Further, the absence of a land bridge at the Straits of Dover is corroborated using molluscan assemblages from the southern North Sea that imply a marine connection between the English Channel and southern North Sea, during highstand, at some point between MIS 12 to MIS 6 (Meijer and Cleveringa, 2009).

The presence of lake waters in the southern North Sea is often considered a precursor to breaching at the Straits of Dover as these lakes provide large quantities of water, and have the ability to release them relatively instantaneously, therefore enabling erosion of the bedrock land bridge (Gibbard et al., 1988; Gibbard, 1995). Reconstructions of lake extent in the southern North Sea during MIS 12 imply the lake covered an area of ca. 140,000 km^2 (Murton and Murton, 2012). These reconstructions are based on the distribution of glaciolacustrine deposits of MIS 12 age in the southern North Sea area (e.g. Long et al., 1988; Gibbard, 2007), and assume that the sediments were deposited contemporaneously across the basin. However, a lack of chronometric data makes it difficult to determine if the lake existed as a single body of water or if it was much more heterogeneously distributed. Further, it is problematic to estimate the duration of lake existence without a chronology.

Enigmatically high positions of fluvial units of MIS 6 age in the Rhine-Meuse basin have been interpreted to reflect periods of high base level due to the presence of a proglacial lake in the southern North Sea (Busschers et al. 2008). Further, a dramatic drop in base level during MIS 6, potentially driven by processes operating at the Straits of Dover and draining of this lake, is recorded in the Rhine-Meuse delta (Busschers et al., 2008). This evidence supports the existence of a southern North Sea lake during MIS 6. However, again it is difficult to reconstruct the lake's extent and chronology. The existence of a southern North Sea lake during MIS 2 is unknown. Coalescence of British and Fennoscandian ice Sheets during MIS 2 (Graham et al., 2011) would have created the conditions necessary for lake development. However, no evidence has been reported to date and it is it is unclear to what extent palaeogeography at the Straits of Dover influenced the potential for lake development.

Assuming the existence of a southern North Sea lake is a key component driving incision at the Straits of Dover, existing evidence would suggest either a MIS 12 or MIS 6 age for breaching. An MIS 12 age for initial breach is most likely. However, it is unclear how much of the land bridge was eroded during this time and what effect the resulting topography had on the timing and duration of marine connections during subsequent highstands. There is sufficient evidence to support erosion at the Straits of Dover during MIS 6. However, a more robust, highly resolved chronological framework of erosional events is required to test competing hypotheses regarding the timing of breaching.

2.3 BREACHING MECHANISMS

In addition to ongoing debates surrounding the timing of erosion at the Straits of Dover, there are discussions about the mechanism that forced initial breaching. Features preserved on the seabed have been interpreted as remnants of a glaciation that advanced onto English Channel continental shelf (Kellaway et al., 1975). However, there is no evidence to support such a southerly limit of ice margins during the Quaternary (Elhers et al., 2011) and this hypothesis is no longer considered plausible in ongoing debates. Two alternative hypotheses have been proposed that include gradual erosion as a result of fluvial downcutting i.e. overspill (Dingwall, 1975; Gibbard et al., 1988; Gibbard, 1995; Busschers et al., 2008) and catastrophic flooding (Roep, 1975; Smith 1985; Gibbard, 2007; Gupta et al., 2007). Both hypotheses propose erosion to be driven by overflow of water from a lake impounded in the southern North Sea basin. However, it is unclear, based on the available evidence, if this erosion was relatively instantaneous, i.e. 'catastrophic', or occurred gradually.

The morphology of the seabed in the eastern English Channel is characterised by a complicated network of palaeovalleys that are incised into bedrock (Fig. 2.1). One of the largest palaeovalleys, the Northern Palaeovalley, appears to be connected to the Lobourg Channel in the Straits of Dover (Fig. 2.1). Therefore an assumption that formation of the Northern Palaeovalley must have been at least partly controlled by the processes responsible for erosion at the Straits of Dover has been adopted (Smith, 1985; Gupta et al., 2007).

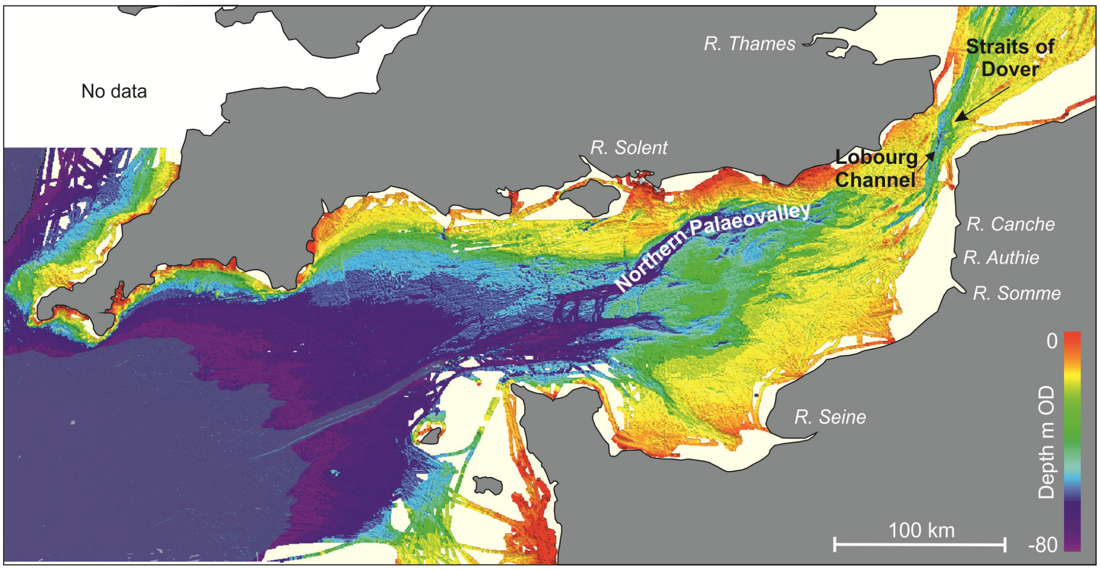


Figure 2.1: Morphology of the seabed in the English Channel. Bathymetry source is Olex, reproduced with the permission of Olex AS.

Smith (1985) made a comparison between the palaeovalleys of the eastern English Channel (including the Northern Palaeovalley) and the channelled scablands in Washington, USA (Bretz, 1969) and concluded that because of their morphological similarities, they must have formed through similar processes. The channelled scablands were sculpted by catastrophic drainage of glacial Lake Missoula when an ice-dam collapsed at the end of the last glacial period (Bretz, 1969). With this in mind, Smith (1985) proposed that the palaeovalleys in the eastern English Channel were created over a short period of time by a catastrophic event linked to drainage of a palaeo-lake. More recently, Gupta et al. (2007) published high resolution bathymetric data revealing the morphology of the Northern Palaeovalley in unprecedented detail. Anabranching bedrock channels, elongate streamlined bedrock islands and erosional grooves were identified, and interpreted as the product of high magnitude flow. Here, comparisons were made between the bedrock bedforms preserved in the Northern Palaeovalley and those associated with the channelled scablands (Fig. 2.2). Again, the similarities observed led to the conclusion that the morphology of the Northern Palaeovalley could have only been created by catastrophic processes. Further, preservation of the Palaeo-Solent as a hanging valley was interpreted as evidence for rapid base-level lowering through channel erosion, and preservation of a sub-horizontal bedrock platform at the margin of the palaeovalley was used as evidence for at least two phases of catastrophic flooding. Finally, calculations of palaeo-discharge using the Manning's equation, based on the morphology preserved, suggested the flood events were "some of the largest on earth" (Gupta et al., 2007).

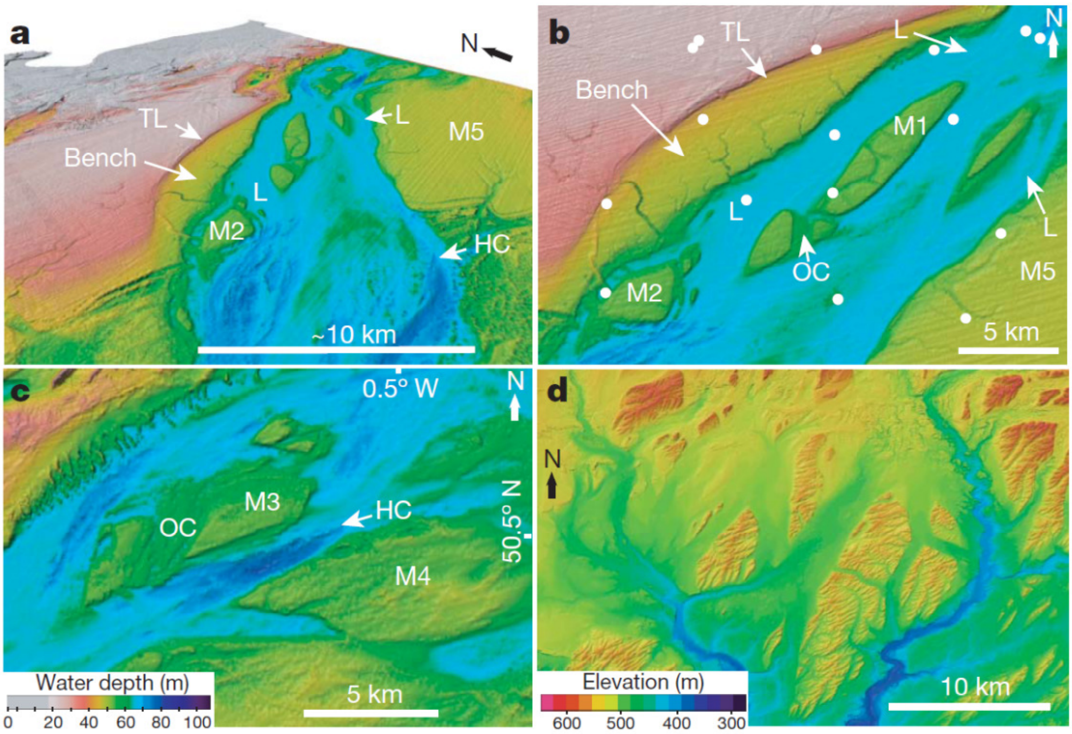


Figure 2.2: Reproduced from Gupta et al., (2007); see article for full figure caption. (a, b and c) morphology of the Northern Palaeovalley (d) morphology of the channelled scablands.

Despite striking similarities between the English Channel palaeovalley complex and the channelled scablands, it is important to consider some of the limitations with the evidence presented to support the catastrophic flooding hypothesis. As highlighted by Gibbard, (1995), drainage of Lake Missoula occurred due to breaching of an ice-dam, whereas the lake in the southern North Sea was impounded by a structural divide in the form of a bedrock ridge. Although chalk is highly susceptible to weathering and dissolution under cold climate regimes (Murton and Belshaw, 2011), the mechanism of breaching cannot be compared. As discussed in section 7.2, the timing of breaching, and thus catastrophic flooding, is linked to periods where there is evidence for lake waters in the southern North Sea (principally MIS 12 and MIS 6). However, there is no independent chronology available to constrain the timing of formation of the Northern Palaeovalley, and its link with erosion at the Straits of Dover. Reconstructions of palaeo-discharges assume the erosional morphology was created by relatively low frequency, high magnitude events rather than through a culmination of processes operating through time. The relative importance of high frequency, low magnitude geomorphic processes in shaping the landscape is often underplayed (Wolman and Miller, 1960) and difficult to distinguish in the stratigraphic record (Goodwin and Anderson, 1985). Again, a chronological constraint on the timing and rate of landscape change would help resolve this.

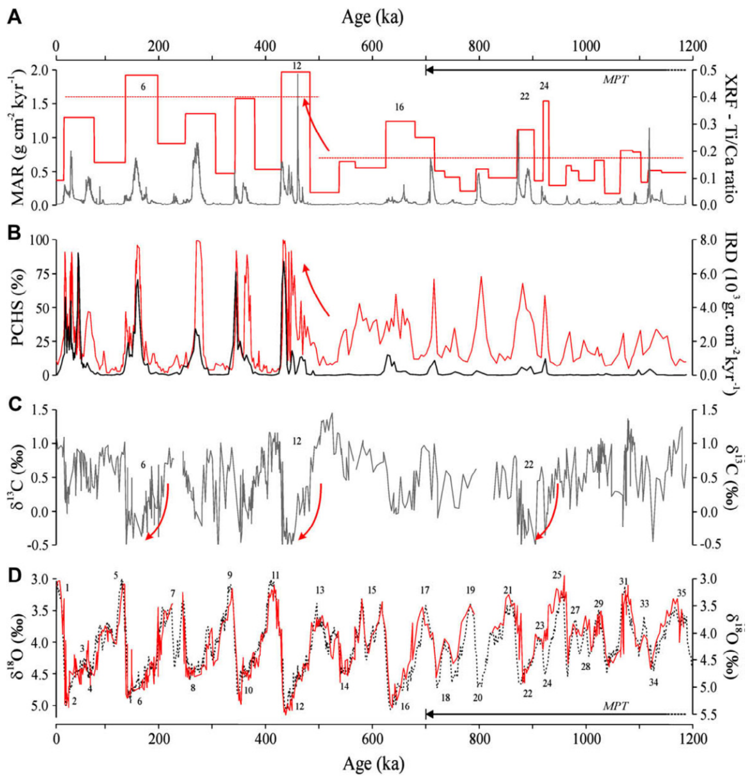


Figure 2.3: Summary of data obtained from a core at the continental margin reproduced from Toucanne et al. (2009a), see article for full figure caption. (a) Terriginous Mass Accumulation Rates (MAR - continuous red line) demonstrating increased sediment input from English Channel rivers from MIS 12 onwards. (b) Ice-rafted detritus (IRD - black line). (c) Benthic δ^{13}C. (d) Benthic δ^{18}O (red line).

As an alternative to the catastrophic flooding hypothesis, it is important to consider the effect gradual erosion through fluvial downcutting had on the landscape. Rather than through an 'instantaneous' flood event, erosion may have been driven by fluctuating lake levels where during periods of 'overspill' (see Gibbard, 1995; Busschers et al., 2008), changes in slope gradient and base-level promoted incision. Incision may have persisted over multiple glacial periods until a base level was reached that coincided with the elevation of the continental shelf in the eastern English Channel. Part of the palaeovalley complex in the eastern English Channel is considered to be of significant antiquity, and to have formed through repeated phases of erosion driven by changing sea levels over the Quaternary period (Dingwall, 1795; Bridgland, 2002; Antoine et al., 2003; Gibbard and Lautridou, 2003; Lericolais et al., 2003). The sedimentary record preserved at the West European Atlantic margin documents variations in discharge from English Channel rivers and identifies periods of enhanced fluvial activity during each glacial period from MIS 12 onwards (Fig. 2.3) (Toucanne et al., 2009a). Reconstructions of palaeo-discharge have been carried out for MIS 2 only (Toucanne et al., 2010) and the chronology is not of a sufficient resolution to resolve if any of these discharges were influenced by catastrophic flood events. Despite the advancements made by the above research, the role of fluvial processes in shaping the landscape, and the persistence of fluvial landforms over glacial-interglacial cycles is poorly understood making it difficult to distinguish between what is 'normal' and what is 'catastrophic'.

Thus far, reconstructions of Quaternary landscape development in the English Channel are based on the interpretation of low resolution seismic data (e.g. Dingwall, 1975; Kellaway et al., 1975) or, high resolution bathymetric data that has not been corroborated with geological data from the subsurface (e.g. Gupta et al., 2007). In addition, with the exception of a few isolated OSL and ^{14}C ages (Gupta et al., 2004; Wessex Archaeology, 2008), there is no chronometric constraint for phases of landscape development. Therefore, a degree of ambiguity is incorporated into geological interpretations which form the basis of present understandings of the Quaternary history of the English Channel.

Chapter 3

Integrating marine geophysics and core data

3.1 BACKGROUND

Remote sensing of the seabed and sub-surface using marine geophysics is a powerful method of exploring landscapes presently submerged beneath the sea (e.g. Gaffney et al., 2007). A range of techniques can be employed to extract geological and geomorphological information. This chapter examines the methodological approach to investigating drowned landscapes using shallow sub-bottom seismic reflection profiles and bathymetric data, calibrated with lithological information from cores.

3.2 SHALLOW SUB-BOTTOM 2D SEISMIC REFLECTION PROFILING

Seismic reflection profiling is a method of remote sensing geological properties of the subsurface, in aquatic settings, using an acoustic source. The velocity of sound as it travels through the sub-surface (acoustic impedance) is principally controlled by lithology (Fig. 3.1a). At boundaries between different lithologies, part of the acoustic wave is reflected. However, it is important to note that the acoustic properties of rocks/sediments can also be altered by inclusions of water or gas within pore space. The technique involves emitting an acoustic pulse from a source, after which, an array of detectors intercepts the reflection and measures the amount of time taken for the acoustic pulse to travel from the source, to the lithological interface, and back again (two way travel time [TWTT]). By emitting pulses at regular intervals along a continuous track, the location of which is recorded using a Global Positioning Systems (GPS), a 2D seismic reflection profile is produced (Fig. 3.1b). Shallow sub-bottom profilers typically operate at frequencies below 10 KHz targeting lithologies at depths up to ca. 50 m below the seabed. Time can be converted to distance using an acoustic impedance that is dependent on lithology (Stewart, 2011), enabling the depths of lithological boundaries to be mapped.

3.3 BATHYMETRY

To determine depth to seabed and thus produce a map of seabed bathymetry, acoustic surveying techniques, principally sonar echo sounding, are widely used. Sonar devices measure the amount of time taken for sound to travel from an acoustic source to the

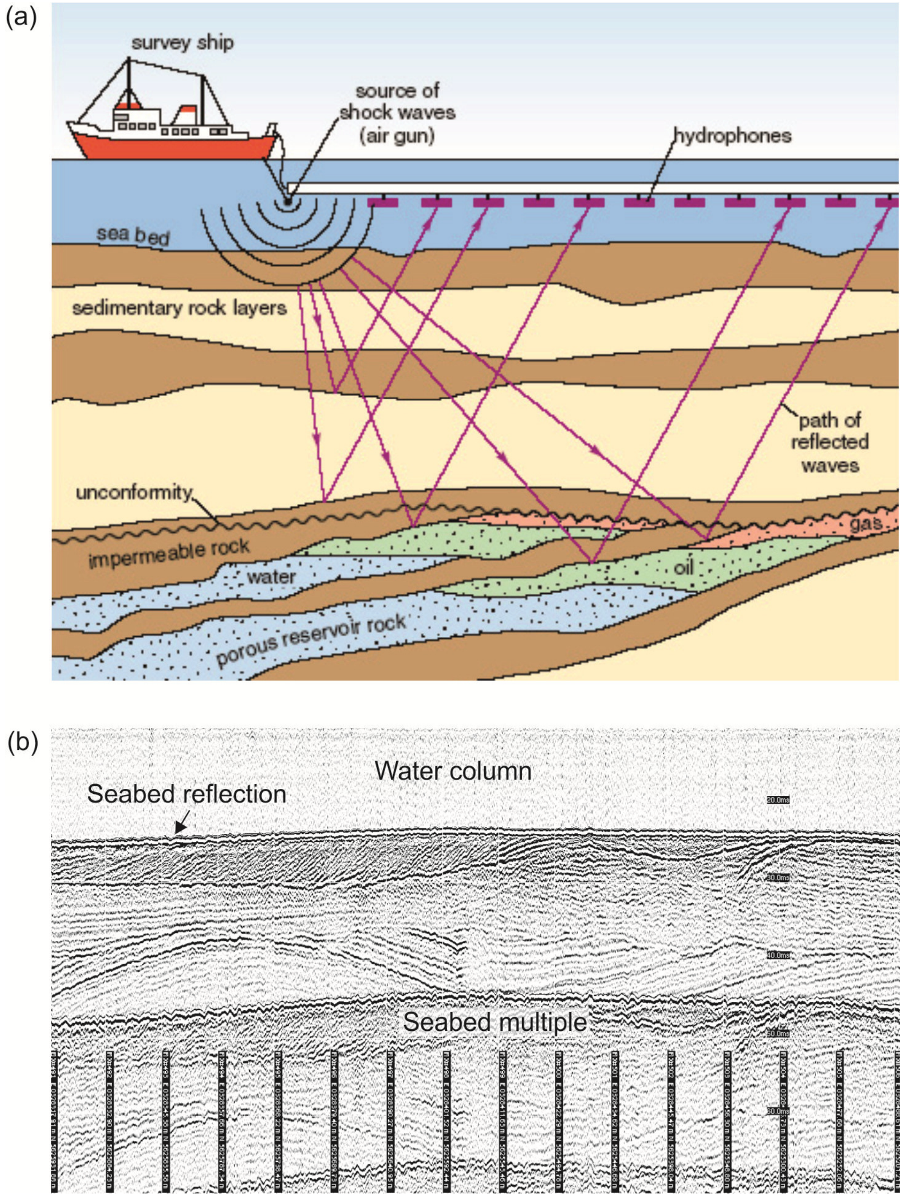


Figure 3.1: (a) schematic illustration of seismic reflection data collection (source: http://www.agilegeoscience.com) (b) example of a 2D seismic reflection profile collected for this PhD. Vertical scale is measured in TWTT. Horizontal scale shows geographic position.

seabed, and back to a sensor. Time is then converted to depth using an acoustic velocity of sound in water, typically 1500 ms^{-1} (Stewart, 2011). A single acoustic pulse or beam measures water depth at a single point on the seabed and determines the location of this point using a GPS. If measured continuously along a vessels track, a 2D image of the seabed is produced.

To convert single beam echo sound data into a 3D bathymetric map, a high spatial resolution of data points is required to permit accurate interpolation between individual soundings. Development of the Olex AS global bathymetry database provided an interface for commercial and private vessels to share single beam echo sound data. In areas of concentrated shipping activity the database provides soundings at distances between 20 m and 200 m (Fig. 3.2).

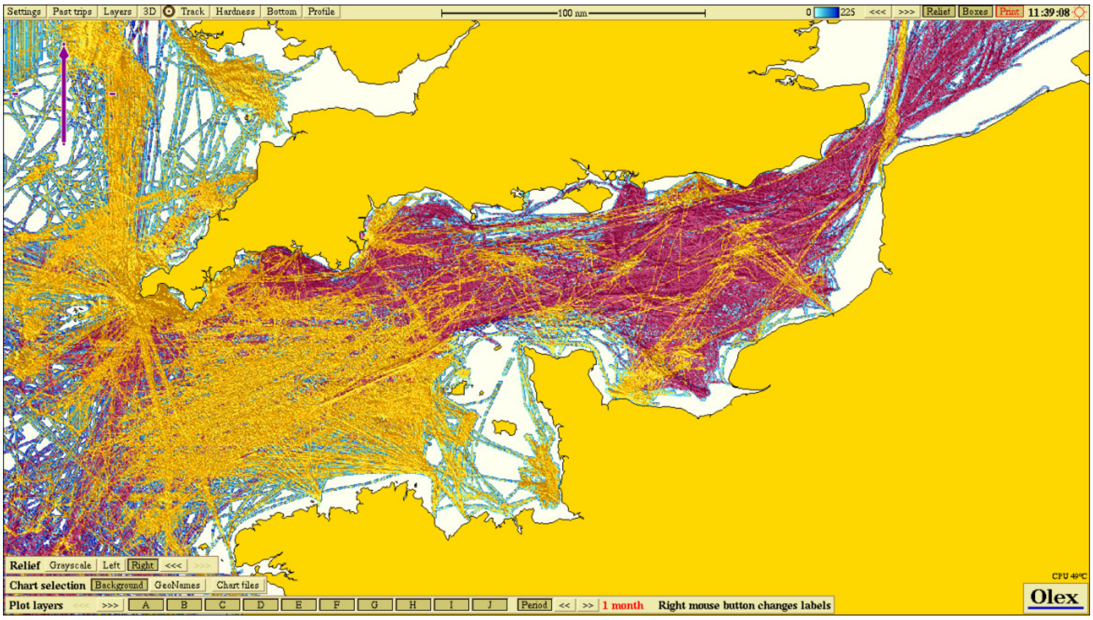


Figure 3.2: Olex software interface. Vessel tracks are represented by pink and orange lines. A high density of data is available for the English Channel.

To resolve changes in elevation on the seabed at a higher spatial resolution, multibeam echo-sounders (MBES) are used. MBES systems emit a beam of acoustic pulses and an array of sensors intercept the returning echo (Fig. 3.3a). Converting time to distance using the MBES survey technique is complex as beam angles continually change as the vessel moves. Differential GPS and precision motion and altitude systems correct for heave, roll pitch and yaw, providing accurate depth data from a 3D 'swath' of the seabed (Fig. 3.3b). A corridor approach to the collection of MBES data where individual swaths overlap presents a high resolution map of seabed bathymetry (Fig. 3.3c).

3.4 VIBROCORING

Vibrocoring is a technique for sampling unconsolidated sediment from below the seabed. The corer is deployed from a vessel (Fig. 3.4) and upon on reaching the seabed, high frequency vibrations reduce friction and drive the core tube into the sediment. Maximum recovery (up to 6 m below seabed) is achieved in unconsolidated homogeneous sediments.

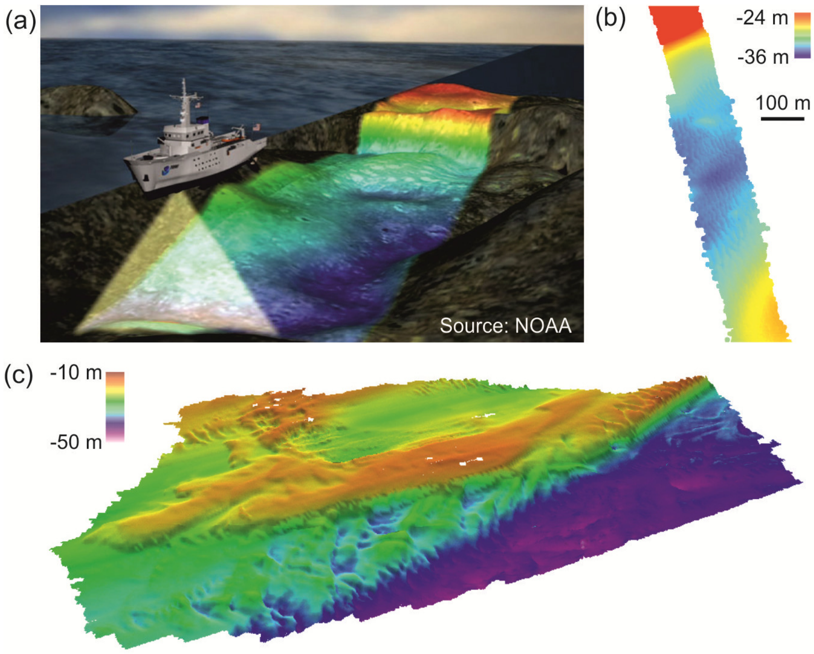


Figure 3.3: (a) schematic visualisation of MBES data collection using a hull mounted system (b) an example of a single swath of MBES data collected for this PhD (c) interpolation of MBES data from multiple swaths (Cazenave, 2007). Shaded relief illuminated from the NW at 45° altitude.

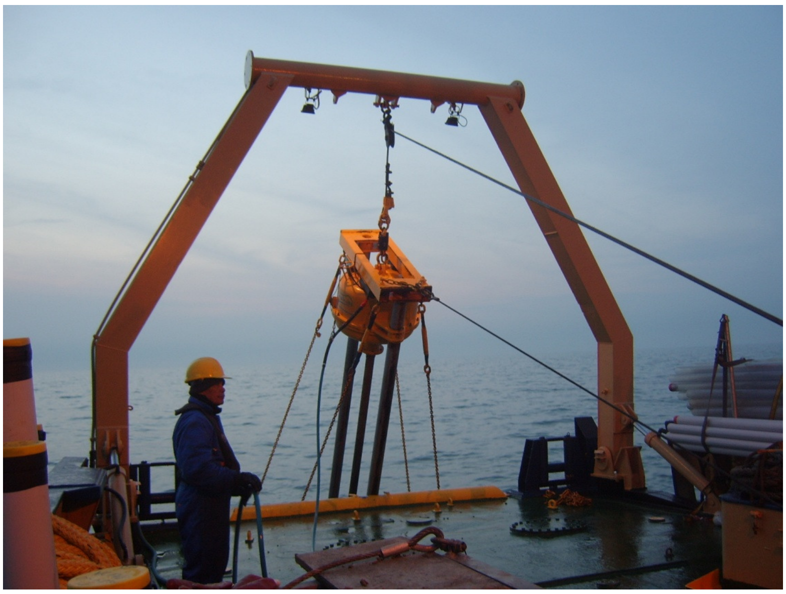


Figure 3.4: Deployment of vibrocorer from MV Flatholme, March 2010.

3.5 DATA INTEGRATION: AN EXAMPLE FROM HASTINGS BANK

The stratigraphic model of landscape evolution presented in this thesis was developed through the interpretation of bathymetric data and shallow sub-surface 2D seismic reflection profiles calibrated with vibrocores. Collectively, the data covers a 5000 km^2 area of seabed in the eastern English Channel. The data were collected over last 20 years by various survey companies with different objectives, and demonstrate variations in quality, format, and resolution, as technologies have advanced over the years. Integrating such a dataset can be problematic. This section aims to demonstrate the process of data integration by working through an example, from initial collection to interpolation, in an area of dense data coverage, at Hastings Bank, in the north-eastern English Channel.

3.5.1 Acquisition and processing

Seismic reflection data

Seismic reflection data were collected during three independent surveys (see Table 3.1 for details and Fig. 3.5 for track plot). All surveys used surface towed boomer sources that operated at high frequencies to produce images with high vertical and lateral resolution (Table 3.1). Surveys A and B were conducted on behalf of aggregate companies between 1990 and 2005. These data were stored as paper records. However, not all survey details (e.g. positioning system), particularly for survey A, were available, thus introducing a degree of uncertainty into the integration process. Survey C was carried out specifically for the research presented in this thesis. The survey report is presented as Appendix A. Navigation information was obtained using DGPS with a horizontal accuracy of 2-3 m. An offset (layback) of 32 m between the DGPS antenna and hydrophone receiver was measured before the survey commenced, and applied to online navigation systems. Data were recorded digitally in the Coda Octopus DA2000 acquisition and processing system.

Bathymetry

Multibeam swath bathymetric data were collected simultaneously with seismic reflection data during surveys B and C. Full details of survey B are given in (Cazenave, 2007). Both surveys used DGPS with a positioning accuracy of <2 m for navigation information. During Survey B, a line spacing of 100 m and a swath width of 7.4 x water depth (m) ensured overlap between individual swaths improving the accuracy of calculations of water depth

Survey (Report number)	Client	Date	Source (frequency)	Positioning (accuracy)	Vertical resolution (m)	Lateral resolution (m)	Layback method	Data Storage
A (Andrews 757-1)	South Coast Shipping	Aug 1990	Boomer	Coastal/radar navigation (not known)	Not known	No known	15m layback applied manually to trackplot	Paper
B (UTEC 534 A)	Resource Management Association	June – Dec 2005	Boomer (1.2-5 kHz)	DGPS (<2 m)	0.09 - 0.35	1.7 - 3.5	15m layback applied manually to trackplot	Paper
C (Emu Ltd J/1/02/1538)	Hanson Aggregate Marine Ltd	Dec 2009– Jan 2010	Boomer (1-4 kHz)	DGPS (<2 m)	0.11 - 0.43	1.9 - 4.2	32m layback applied to online navigation system (positioning accuracy same as DGPS)	Digital (.cod)

Table 3.1: Seismic reflection survey details

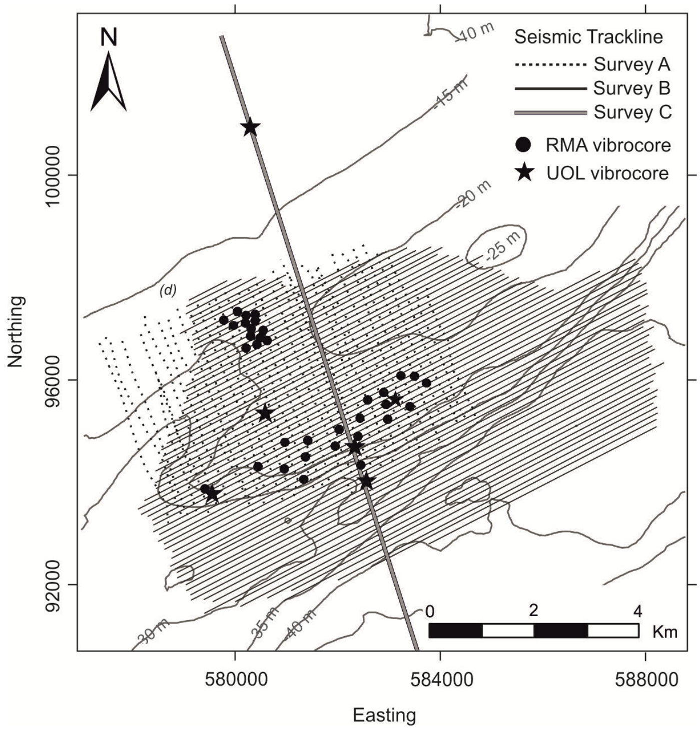


Figure 3.5: Location of seismic reflection profiles and vibrocores. RMA – Resource Management Association, UOL – University of Liverpool. Coordinates WGS84 UTM Zone 31N.

(Cazenave, 2007). After correction for navigation error and tidal offsets, the data were provided as a 1 m raster grid for use in Arc GIS and are given in Fig. 3.6a. During survey C a single swath of bathymetric data was collected (Fig. 3.6a). A Reson Seabat 8125 multibeam system was used in conjunction with a POS MV precision motion and altitude system. Post-processing was carried out using QINSy processing software and relevant corrections and filters were applied including patch test calibration results, removal of outliers with automatic and manual filtering, and post-processing of tidal data. The data were gridded at 1 m cell size using Kriging in Arc GIS and given the precision of the acquisition system, depth could be resolved to a cm.

A visual comparison between the two bathymetry datasets used revealed areas on the seabed where water depths differ (Fig. 3.6b). To quantify this difference, the variance in water depth between the two datasets was calculated using ArcGIS and is given in Figures 3.6c, 3.6d and 3.6e. The greatest variance (up to 4 m) is observed in areas of intensive dredging (Fig. 3.6c), near slopes (Fig. 3.6d), or, in the region of constructional bedforms i.e. sediment waves (Fig. 3.6e). This is most likely due to differences in post-processing data handling. It can be corrected by re-processing both datasets using the same standards. However, as most variance occurs in areas not used in final interpolations, i.e. dredged areas and bedform fields, this is considered unnecessary for the purpose of this thesis. To ensure consistency throughout, all stratigraphic information was tied to bathymetric data collected during survey B (Cazenave, 2007).

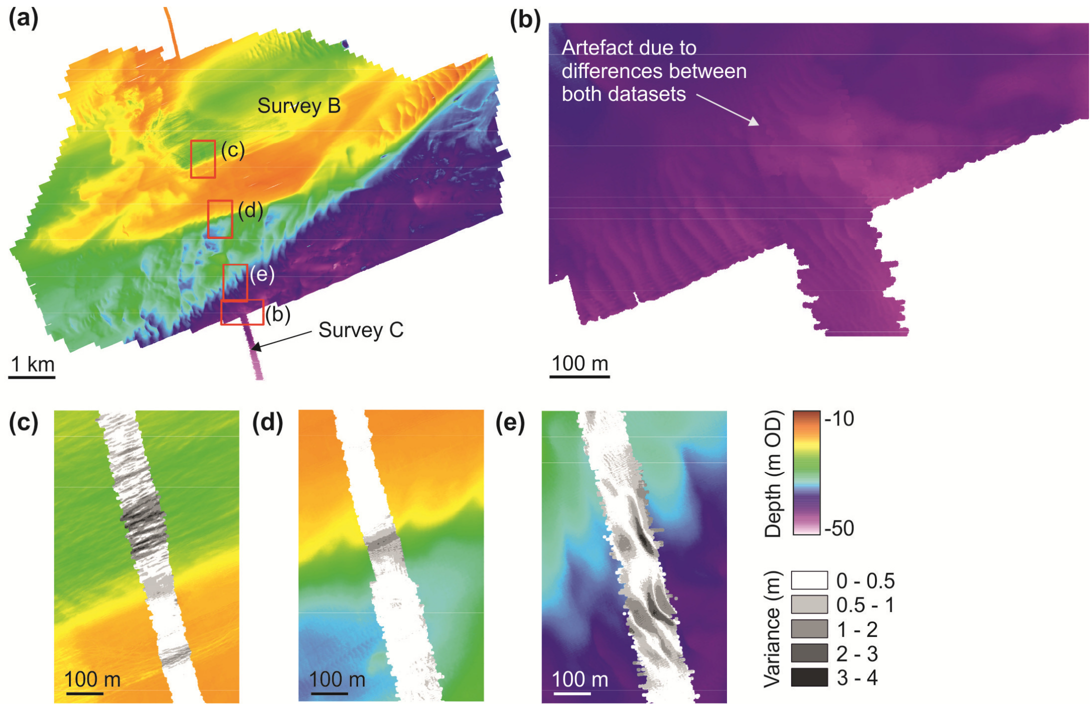


Figure: 3.6: (a) bathymetry collected during survey B and survey C. (b) data from survey B overlain with the single swath of data collected during survey C. Variation in water depth between the two surveys is represented by discontinuity in sediment wave morphology. (c) (d) (e) variance in water depth where survey C overlies survey B.

Cores

As part of aggregate prospecting and monitoring surveys, 36 vibrocores tied to seismic lines were recovered from the Hastings Bank region during surveys in 2003 (Fig. 3.5). The vibrocores were photographed, logged and sampled for geotechnical purposes, and the reports made available for analysis as part of this thesis (see Appendix B for examples of vibrocore datasheets). Targeted positioning of the vibrocores by aggregate companies has led to an irregular distribution of cores and a bias towards coarser grained sediments.

To corroborate existing vibrocore records an additional 6 vibrocores were collected during March 2010. The cores were collected using a high-powered C-CoreHP vibrocorer and recovered in 85 mm-diameter opaque plastic liners. An offset between the vibrocorer and the DGPS antenna was measured and applied to navigation information. Maximum penetration of the vibrocorer was 5 m, with a maximum recovery of 2.70 m due to the coarse nature of sediment. Cores were immediately sealed and transported to the laboratory where they were split, logged, photographed and sampled. The depth of samples relative to OD was determined using bathymetry data assuming the top of the core corresponded to the seabed. The vibrocore survey logs are presented in Appendix C and vibrocore logs and photographs given in Appendix D.

3.5.2 Data analysis and interpretation

Seismic reflection data

Seismic stratigraphic analyses were carried out according to the criteria outlined by Mitchum et al., (1977). Each seismic profile was visually inspected to characterise key seismic facies based on reflector amplitude, frequency, continuity and geometry. Seismic units were then identified as packages of genetically related seismic facies bounded by laterally extensive surfaces.

The success of recognising seismic facies and units on seismic profiles from different surveys depended on the quality of the data and the alignment of profile tracks relative to the sediment body. The quality of data is influenced by a variety of factors including weather during survey, water depth, acoustic source frequency, lithology, (and materials contained therein, e.g. tree stumps and boulders) and post-processing and filtering. Many of these factors are determined during the survey and cannot be altered afterwards. When using seismic data that are only available as paper records, the seismic profile cannot be enhanced and interpretations are limited by the quality of the data produced during the survey. If seismic data are recorded digitally it is possible to post-process the data and enhance the seismic profile by targeting specific time windows of interest. An example of the difference in data quality between Survey B and Survey C is given in Fig. 3.7. Identifying seismic facies and seismic units using the data collected during Survey B was difficult due to the low amplitude nature of reflectors.

By collating seismic data from Survey B and Survey C, an orthogonal grid of closely spaced (80 – 120 m) seismic lines was created. Interpretation of seismic units according to their association with seismic facies was different for each survey. An example of intersecting seismic profiles is presented Fig. 3.7. Where possible, interpretations were made using cross lines to correlate seismic reflectors and provide a 3D perspective on seismic facies architecture. Figure 3.7 demonstrates that the geometry of a seismic unit and its reflector configuration can vary depending on the angle at which the track line intersects the feature. If a single line were to be interpreted in isolation, the resulting geological interpretation may be flawed.

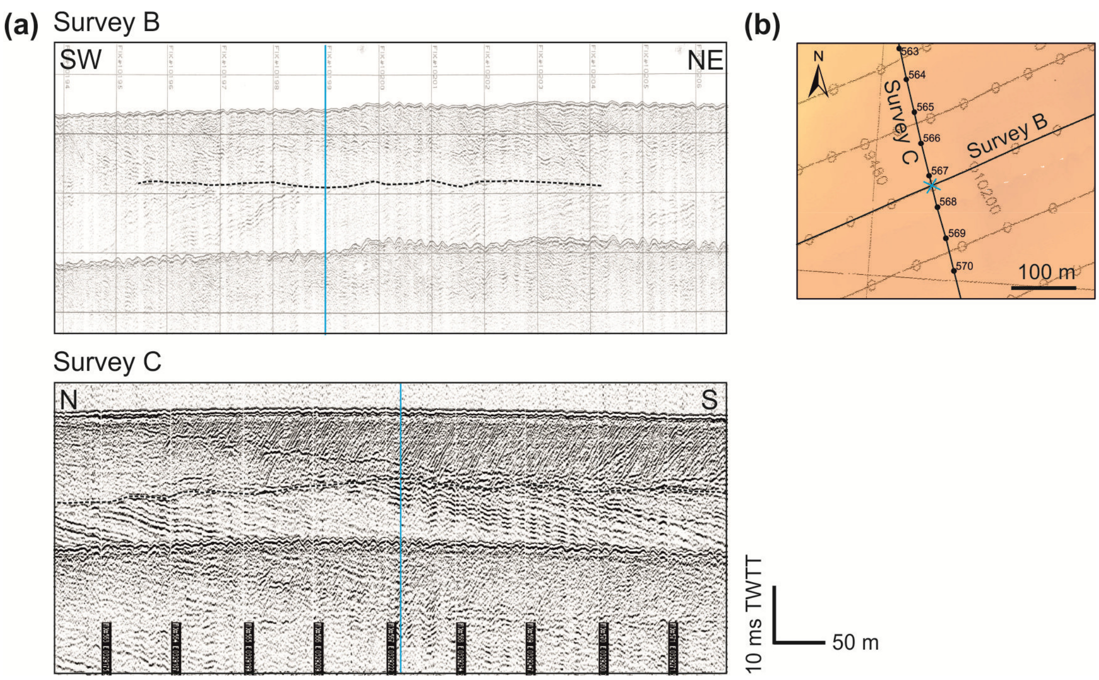


Figure 3.7: (a) seismic data from intersecting profiles. The blue line locates the intersection point. The dashed line is a strong reflector marking the interface between solid and unconsolidated geology. (b) Location of seismic profiles.

Once seismic units were identified, the thickness of each unit could be measured. This was carried out on paper records (Survey A and Survey B) by manual measuring the depth in ms TWTT from the seabed to the lower bounding surface of each unit. Given the vertical scale defined during each survey, it was possible to resolve seismic unit thickness at ca. 1 ms TWTT. For Survey A and B, seismic unit thickness was measured spatially at 70 m intervals, both of which coincided with fix points on the seismic profile. The spatial reference of fix points was established by digitising track plots produced during each survey, using Arc GIS. Seismic unit thickness data from Survey A and Survey B were stored in a geodatabase as xyz data. Analysis of digital seismic data (Survey C) using Coda software enabled unit thickness to be measured by tagging reflectors and exporting information as xyz data for incorporation in Arc GIS. Here, the interval spacing varied and depended on the number of points tagged in each file. For Survey C, interval spacing was between 5 m and 20 m, and the vertical scale was resolved at <1 ms TWTT. Both methods of interpretation are qualitative. However, by using digital data, it is possible to resolve unit thickness at higher spatial and vertical scales.

Bathymetry

The bathymetry data was interpreted to characterise morphological areas of the seabed, i.e. valleys and sediment waves. Spatial analysis of the seabed was carried out using Arc GIS to define slope angles. Topographic profiles were produced to help with morphological interpretations. Further, drainage configurations and channels were mapped using the hydrology function in ArcGIS.

Cores

Core logs and photographs from aggregate prospecting surveys were interrogated to characterise lithofacies depending on lithology and sedimentary structures. These lithofacies were ground-truthed using the cores collected as part of this research. An assessment of depositional environment for each lithofacies was made according to diagnostic sedimentary features, e.g. high concentrations of marine shells. In places, sediments were sampled for partical size, petrographic and palaeoecological analyses. This information was used to support environmental interpretations.

3.5.3 Data interpolation

Seismic reflection data

After identifying key seismic units and determining their thickness using multiple cross-cutting seismic profiles, isopachs of sediment thickness for each unit were produced using Arc GIS. This involved interpolating between data points using Kriging in Arc GIS. A cell size of 25 m was chosen and semi-variograms were produced to show areas where the interpolation was less certain due to a low spatial resolution of points (Fig. 3.8). Interpolating seismic unit thickness in areas that have undergone dredging activities in the time period between the collection of survey A and survey B, was problematic. These areas were identified by the presence of dredging scars on bathymetry data and highly chaotic reflectors on seismic profiles. Seismic unit thickness data interpreted from seismic profiles collected during survey A, i.e. post-dredging, were not included in the interpolation process.

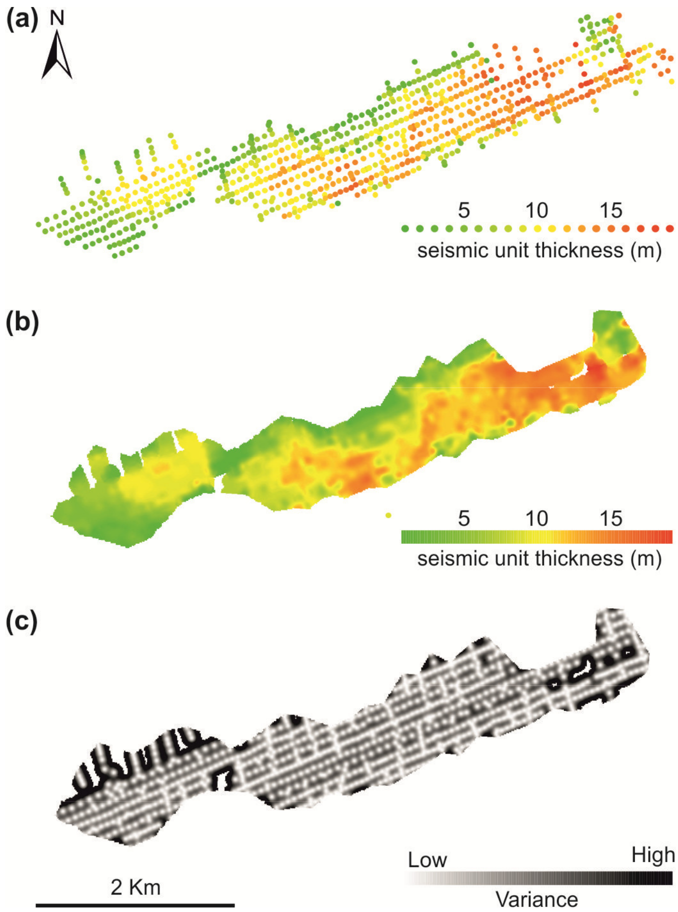


Figure 3.8: an example of the interpolation process (a) distribution of point data (b) interpolation surface (c) variogram showing confidence in the interpolation method. The interpolation method is less certain in areas of high variance.

Thus far, seismic unit thickness has been measured in ms TWTT. To map the geometry of seismic units relative to the seabed, time was converted to distance in metres using the following calculation;

$$d = (t/2)*v \qquad \text{where, } d = \text{distance (m)}$$
$$t = \text{time (ms TWTT)}$$
$$v = \text{acoustic velocity } (1700\ m\ s^{-1})$$

This calculation could be quickly applied to all data using raster calculator in Arc GIS.

3.5.4 Data integration

The geometry of seismic units was interpolated by subtracting seismic unit thickness from seabed bathymetry, thus producing a basal surface relative to OD. This was only possible in areas where the top of the seismic unit was concordant with the seabed (e.g. Fig. 3.9a).

Where seismic units exhibited erosional truncation at their upper surface, i.e. they were cut by younger seismic units, only the thickness of the unit could be mapped (Fig 3.9b). To establish the geometry of the bounding surface that separates bedrock from unconsolidated sediment, maximum sediment thickness, as opposed to seismic unit thickness, was subtracted from seabed bathymetry. Sediment thickness was gridded at 25 m cell size and subtracted from a 1 m bathymetry grid. Therefore, seabed features that are <25 m in size appear as artefacts on the resulting interpolation surface (Fig. 3.9c).

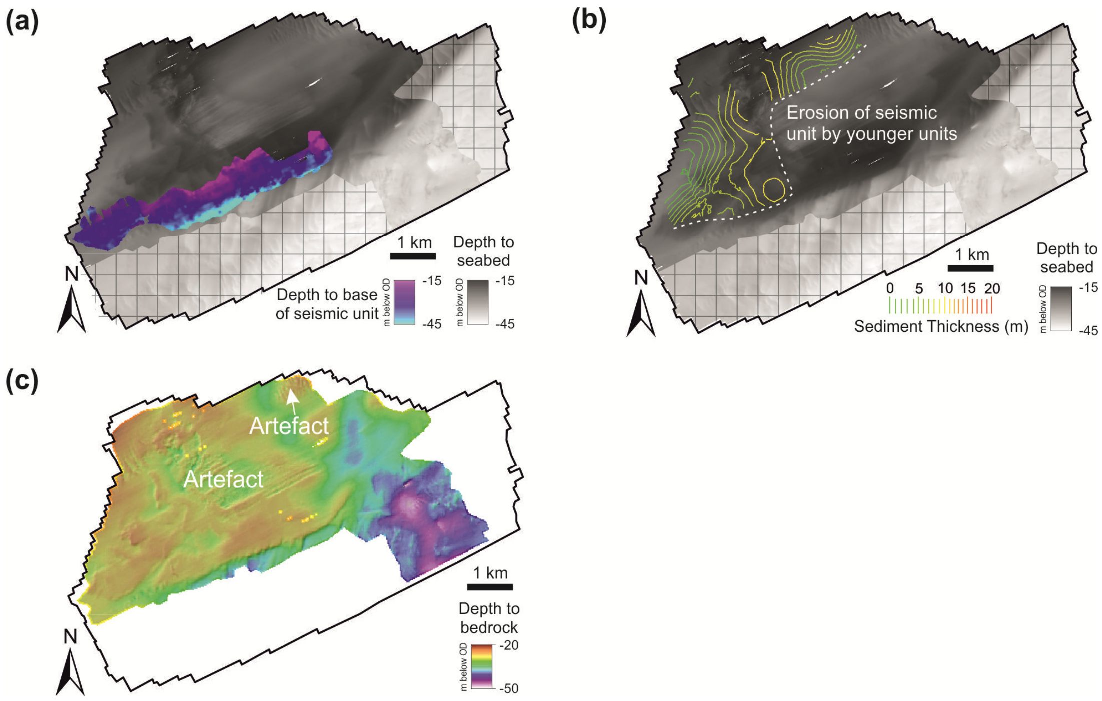


Figure 3.9: (a) a representative example showing the geometry of the base of a seismic unit relative to OD calculated by subtracting seismic unit thickness from seabed bathymetry (b) seismic unit thickness (m) mapped independent of OD (c) the geometry of the surface separating bedrock from unconsolidated sediment, mapped relative to OD.

Integrating seismic data with lithological information from cores is a means of ascribing geological attributes to acoustic data. For example, Seismic Unit A (Fig. 3.10) exhibits different acoustic properties to Seismic Unit B (Fig. 3.10) suggesting different lithological properties. Vibrocores recovered from each seismic unit confirmed this (Fig 3.10). Sediments from Seismic Unit A produce high amplitude, oblique to chaotic reflectors and are coarse clastic in nature. Alternatively, finer grained sandy sediments produce lower amplitude, more continuous reflectors, characteristic of Seismic Unit B. Using vibrocores to calibrate seismic data at depths >5 m is not possible. Further, smaller scale changes in lithology observed within a core cannot be resolved using seismic data alone. Therefore, only by integrating both seismic and core data, a more complete understanding of sub-surface geology can be established.

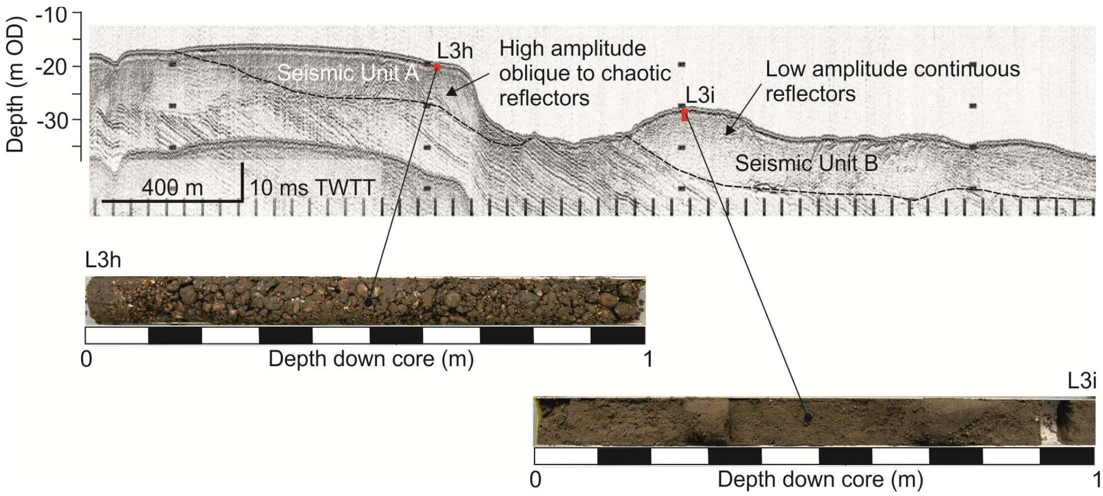


Figure 3.10: Integration of core data with seismic data.

3.6 Methodology

The methodological approach to integrating geophysics and core data presented in this chapter was applied across the entire eastern English Channel study area. However, there were some limitations conditioned by the availability and quality of data. It was not always possible to map seismic facies and units across seismic profiles due to the wide spacing (locally up to 10 km) of lines, the poor quality of some data, and/or, the highly variable nature of acoustic reflectors. As a result of more widely distributed data points, Interpolation of seismic unit thickness and sediment thickness was carried out at a lower spatial resolution (250 m grid size) than the example presented above. The distribution of cores was sporadic and it was not possible to calibrate all seismic units with lithological information. Further, cores made available for analysis were of poor condition and degraded making it difficult to characterise lithofacies. Despite these limitations, collectively, the data presented in this thesis are the best available for the eastern English Channel providing a strong foundation for stratigraphic models and reconstructions of landscape evolution.

Chapter 4

Preservation of a drowned gravel barrier complex: a landscape evolution study from the north-eastern English Channel

Abstract

Landscape response to post-glacial relative sea level during the Quaternary is documented using an integrated dataset of multibeam bathymetry and 2D seismic reflection profiles from the Hastings Bank area in the north-eastern English Channel. Mapping of nine seismic stratigraphic units calibrated to lithological information from multiple vibrocores, has enabled the interpretation of fluvial, shoreface, barrier, washover fan, back-barrier and tidal environments of deposition. The interpreted landscape evolution is as follows: (i) fluvial incision of bedrock during sea-level lowstand; (ii) progradation of a shoreline and then development of a barrier complex as sea-level rose; (iii) recycling and breaching of the barrier; (iv) rapid drowning of the barrier complex; (v) landward migration of the shoreline through continued sea-level rise; and (vi) complete abandonment and submarine preservation of the barrier complex during sea-level highstand. The previously undocumented, yet exceptionally well preserved, drowned barrier complex at Hastings Bank records phases of barrier initiation, breakdown and retreat, and documents coastal response to high rates of relative sea-level rise. Initial development of the barrier complex required a sufficient supply of sediment, maintained by offshore sources, to keep pace with rising sea level, that permitted progradation of a shoreline and development of a barrier complex. Inherited topography in the north-eastern English Channel is an important factor in the development of the barrier complex. Phases of barrier breakdown occur when sediment supply is outpaced by a rapid increase in accommodation controlled by existing basement morphology and rising sea levels. Subsequently, the barrier responds through internal reorganisation by breaching and reworking of existing sediment bodies. Barrier retreat is characterised by a phase of 'sediment surplus' overstepping under rapid rates of sea-level rise where increased water depths limit wave reworking, followed by a phase of discontinuous retreat where the shoreline steps back through 'sediment deficit' overstepping. Hastings Bank presents a rare oppurtunity to examine the conditions and

processes that control barrier response to sea-level rise and, to assess the preservation potential of barrier deposits as a function of the style of retreat.

4.1 INTRODUCTION

Many examples of landscapes that were submerged and preserved by post-glacial sea-level rise have been identified due to advances in geophysical survey techniques and increasing availability of commercially-acquired data (Browne, 1994; Fitch et al., 2005; Storms et al., 2008; Shaw et al., 2009; Kelley et al., 2010; Timmons et al., 2010). These drowned landscapes and their component landforms are important sedimentological and geomorphological archives that are the basinward equivalent of deposits preserved on land. Study of these preserved landscapes can be a means for better predicting coastal landscape response to future climate change by providing important constraints on our understanding of how systems respond to abrupt environmental change. When continental shelves emerge in response to relative sea-level fall in ice-marginal settings, fluvial and periglacial processes become the principal factors shaping the landscape. Commonly, the deposits preserved on the continental shelf in these settings are limited to former river valleys and their associated interfluve/terrace surfaces (Velegrakis et al., 1999; Lericolais et al., 2003; Proust et al., 2010). Preservation of coastal landforms on continental shelves is rare due to their susceptibility to reworking and erosion as the shoreline migrates landward during trangression (Shaw, 2005). Recent exploration of continental shelves, however, has uncovered an increasing number of early Holocene coastal landscapes (Gaffney et al., 2007; Storms et al., 2008; Hijma et al., 2010) suggesting that the conditions required for preservation of these landscapes are not as unique as once assumed. Comprehensive stratigraphic and sedimentological analysis of such submerged landscapes provides the necessary data with which to constrain the conditions, i.e. rate of sea-level rise, basement topography and sediment supply, under which coastal landforms may become submerged.

The English Channel continental shelf is a fluvial basin that has been periodically flooded by the sea during the Quaternary (Lagarde et al., 2003). Consequently the shelf floor is dissected by a complicated network of palaeovalleys (Shepard-Thorn, 1975; Smith, 1985; Bridgland, 2002; Antoine et al., 2003; Lericolais et al., 2003; Gupta et al., 2007). The present day coastline of the north-eastern English Channel is fringed by a range of coarse clastic barriers and associated back-barrier environments (e.g. Dungeness (Hey, 1967; Greensmith and Gutmanis, 1990; Long et al., 2006; Plater et al., 2009); Start Bay (Hails, 1975); The Crumbles Shingle (Jennings and Smyth, 1987); and Chesil Beach (Bennett et al., 2009; Carr and Blackley, 1973)). The presence of early Holocene barrier deposits offshore of Start Bay (Hails, 1975) indicates conditions were suitable in this setting for preservation of submerged coastal deposits. Preservation of deposits offshore of other barrier systems on the English Channel coast have not yet been documented.

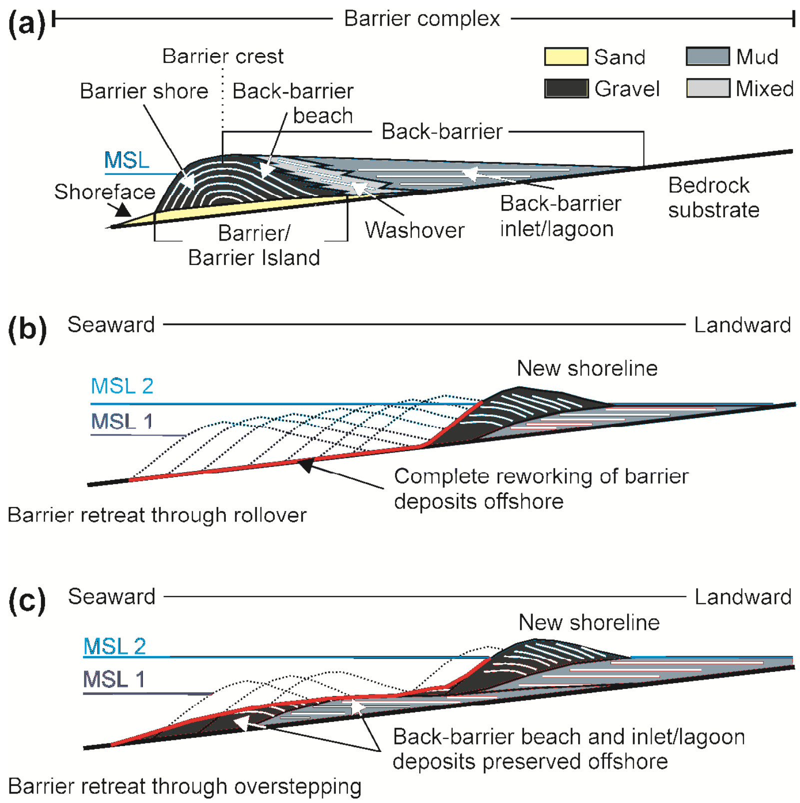


Figure 4.1: (a) Classification of landforms and sedimentary environments associated with a gravel-dominated barrier complex. MSL is mean sea-level. (b) Conceptual model of barrier retreat through rollover. As the shoreline retreats continuously from a position at MSL 1 to MSL 2 the shoreface and barrier beach is reworked and no deposits are preserved offshore of the new shoreline. (c) Conceptual model of barrier retreat through overstepping. As the shoreline retreats discontinuously from MSL 1 to MSL 2, disequilibrium between the conditions forcing barrier retreat encourage shoreline displacement and back-barrier deposits are preserved offshore. For both a and b, the dashed line shows the position of former shorelines, an erosion surface is represented by the red line and white lines are time equivalent depositional surfaces.

The term 'barrier' refers to a range of coastal landforms that have evolved under the predominant influence of waves and net sediment transport pathways (e.g. Plater and Kirby, 2012). A barrier complex or system is defined according to the presence of an attached barrier and/or barrier island that is separated from the mainland by backbarrier lagoons/tidal inlets (Oertel 1985). Principal morphological and sedimentological elements of a gravel-dominated barrier complex, classified according to Otvos (2012), are summarised in Fig. 4.1a, and include shoreface, barrier, washover and back-barrier tidal inlet/lagoon landforms. Barrier formation at the most rudimentary level can be explained through the interactions between wave energy, sediment supply (and transport vector), accommodation space and rates of relative sea-level change (Roy et al., 1994). The preservation potential of transgressive barrier deposits is a function of the style of retreat and considered to be relatively low in comparison to deposits associated with regressive coasts (Storms and Swift 2003). During sea-level rise, barriers retreat landwards either through continuous landward migration (rollover) where there is complete reworking of barrier deposits offshore (Swift and Moslow, 1982; Leatherman et al., 1983) (Fig. 4.1b) or through a process of overstepping where there is a landward displacement of the shoreline and partial preservation of back-barrier deposits offshore (Rampino and Sanders, 1980; Rampino and Sanders, 1982; Leatherman et al., 1983; Forbes et al., 1991; 1995; Storms et al., 2008; Hijma et al., 2010) (Fig. 4.1c). Gravel-dominated barriers are more resilient to relative sea-level rise than their sandy counterparts (Long et al., 2006), therefore, continental shelves offshore of present-day gravel-dominated coasts, such as the English Channel, are potential field sites for exploring the conditions required for drowning and preservation of coastal landscapes, with the findings providing an important evidence base for future coastal resource planning.

An integrated dataset of multibeam swath bathymetry and a network of 2D reflection seismic lines calibrated to multiple vibrocores has permitted identification of a previously undocumented, yet exceptionally well preserved, submerged barrier complex at Hastings Bank in the north-eastern English Channel. Here we provide a high resolution stratigraphic framework for deposition at Hastings Bank that is used to reconstruct late Quaternary landscape evolution and explore the interactions between the factors controlling barrier initiation, breakdown, submergence and preservation.

4.2 SETTING

Hastings Bank is a flat area of seabed that presently lies in shallow water depths (<20 m) in the north-eastern English Channel (Fig. 4.2). Part of Hastings Bank is a licensed aggregate extraction area that has been dredged for sand and gravel resources since the early 1990s (BMAPA and The Crown Estate, 2007). The coarse clastic nature of sediment has long been recognised (Hamblin et al., 1992) and the area is referred to on maps as Hastings 'Shingle'

Bank. However, little is known about the origin and development of the bank, so the term shingle will not be used herein. Hastings Bank is an isolated feature that lies ca. 15 km offshore from the present-day British coastline between Beachy Head and Dungeness (Fig. 4.2). It forms the southernmost extension of a shallowly dipping (<0.2°) planar surface that deepens abruptly (from -20 m to -55 m) at the margin of one of the most prominent morphological features in the English Channel, the Northern Palaeovalley (Smith, 1985). Seafloor morphology in the eastern English Channel is characterised by a complicated network of palaeovalleys (Dingwall, 1975; Smith, 1985) that, in part, formed through fluvial incision when present-day rivers extended offshore in response to base-level fall during Quaternary cold phases (Bellamy, 1995). Formation of the Northern Palaeovalley has been linked to catastrophic drainage through the Straits of Dover during the Middle Pleistocene (Smith, 1985, 1989; Gupta et al., 2007). The English Channel continental shelf has been periodically flooded by post-glacial sea-level rise during the Quaternary leaving behind a complicated sedimentary record that is an amalgamation of fluvial, coastal and marine deposits.

Bedrock geology is controlled by Cretaceous strata of the Weald-Artois anticline (Hamblin et al., 1992). Chalk, Lower Greensand and Weald Clay outcrop at cliffs on the present day coast to the north of Hastings Bank. Significant thicknesses of coarse sediment (<30 m) are usually limited to submerged palaeovalleys offshore or fringing the present day coastline of southeast England (Anthony, 2002). Although the distribution and composition of seabed sediments is relatively well constrained (Cazenave, 2007; James et al., 2011), and the overall thickness of Quaternary deposits has been mapped (Hamblin et al., 1992), the sedimentary processes and environments of deposition preserved in the stratigraphy are poorly documented.

In terms of present-day hydrodynamics, the English Channel is a tide-dominated shelf where sediment transport by waves is limited to water depths of only a few metres (Grochowski et al., 1993). In shallow water depths, significant wave height (H_s) during calm conditions is typically <1 m (Grochowski and Collins, 1994), and during storm events with a return period of 1 year, ~4 m (Henderson and Webber, 1978). Waves are principally derived from the Atlantic Ocean and propagate through the eastern English Channel in a SW-NE direction (Bray et al., 1995). The Hastings Bank area has a moderate tidal range of ca. 2-3 m (Anthony, 2002). Large parts of the English Channel, particularly to the west of Hastings Bank, are sediment-starved and bedrock is at or close to the seabed (James et al.,

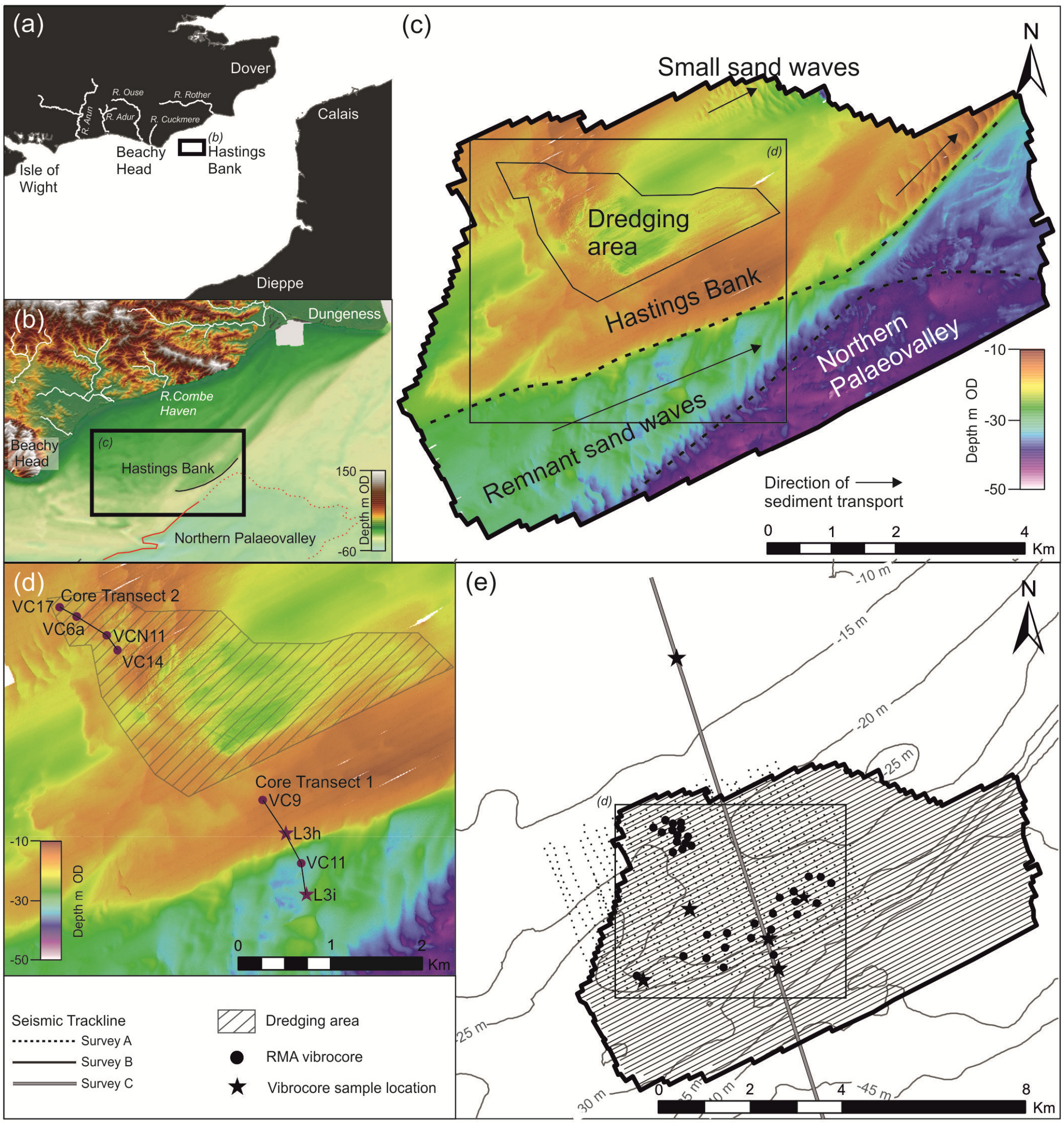


Figure: 4.2: Study area (a) location of Hastings Bank in English Channel; (b) seamless land-sea elevation model for north-eastern English Channel highlighting key morphological features (Digital terrain model ©Intermap Technologies. NEXTMap Britain: Digital terrain mapping of the UK. NERC Earth Observation Data Centre, 2011. Bathymetry © British Crown and SeaZone Solutions Limited. All rights reserved. Product license No. 112010.009); (c) high resolution (1 m grid) bathymetry of Hasting Bank (Cazenave, 2007). Thick black line delimits interpolation grid; (d) locations of vibrocore transects (see Fig. 4.8) including dredging area after BMAPA and The Crown Estate (2007); (e) trackplot showing location of seismic reflection profiles and vibrocores. Thick black line delimits interpolation grid.

2011). These areas are coincident with a bedload parting zone where the strongest tidal currents in the English Channel are recorded (Reynaud et al., 2003). At Hastings Bank, sand is mobile under present day tidal regime (Dix et al., 2007) and is transported north eastwards towards a bedload convergence zone within the Dover Straits (Grochowski et al., 1993).

In the English Channel, the tidal regime is considered more important than wave climates in transporting sediment at the sea-bed (Kenyon and Stride, 1970; Grochowski et al., 1993: Reynaud et al., 2003). However, during the early Holocene when water depths were shallower, the effect of wave climate on large scale sediment transport was more important than observed today (Neill et al., 2009). In comparison to present-day tidal regime, tidal amplitude during the early Holocene is predicted to have been lower (Uehara et al., 2006). In addition, tidal currents reconstructed for 8 ka are predicted to have been three times greater (Uehara et al., 2006) corresponding to the time when Atlantic waters reconnected with the southern North Sea through the Straits of Dover (Shennan et al., 2000).

4.3 METHODS

4.3.1 Seismic data acquisition and interpretation

The seismic data comprise 619 line–km of shallow, sub-bottom Boomer 2D seismic data collected over three surveys (herein referred to as surveys A, B and C) that have been made available by the Resource Management Association (RMA, comprising CEMEX UK Marine Ltd, Hanson Aggregates Marine Ltd and Tarmac Marine Dredging Ltd) (Fig. 4.2). The surveys used surface-towed boomer sources operating at frequencies of 1-5 kHz that penetrate and resolve unconsolidated sediments up to ca. 50 m below the seabed. Within unconsolidated sediments, this provided a lateral resolution of 1.9 m to 4.2 m and a vertical resolution (1/4 wavelength) of 0.08 m to 0.43 m. Positioning accuracy for each of the surveys was <2 m. An orthogonal grid (interpolation grid) of closely spaced (80 – 120 m), NNW-SSE and NE-SW trending seismic reflection profiles (Fig. 4.2) permits integration and correlation between datasets. Interpretation of seismic reflection profiles at this resolution can resolve the nature, extent and thickness of stratigraphic units. Disturbance of sediment due to dredging activities between individual seismic surveys has led to discrepancies in seismic signatures leading to uncertainty in interpretations within the active dredge zone. Seismic traces from Survey A and Survey B are in the form of analogue paper records and no post-acquisition processing of the seismic pulse was possible. Seismic data from Survey C were logged and processed digitally in the Coda Octopus DA2000 system and were available as

Coda digital boomer files for post-acquisition processing. Interpretation of seismic stratigraphy is based on Mitchum et al. (1977). High amplitude seismic reflectors separating stratigraphic units have been correlated from line to line across the grid, digitised manually on both analogue and digital records and imported into ArcGIS. Interpolation between cross-lines was carried out using kriging, and isopachs outlining unit geometry (25 m cell size) and thickness (1 m contours) were plotted. Morphology of the bedrock surface was mapped by subtracting unconsolidated sediment thickness from a 1 m grid of the present-day bathymetry. Artefacts of dredging activities and seabed morphology can be seen due to differences in the resolution of interpolated surfaces. Acoustic velocity surveys were carried out in the Hasting Bank region (UTEC, 2005) and typical values for seawater were 1505 ms^{-1}. An acoustic velocity of 1700 ms^{-1} for subsurface sediments was used to convert two way travel time (TWTT) to depth in metres.

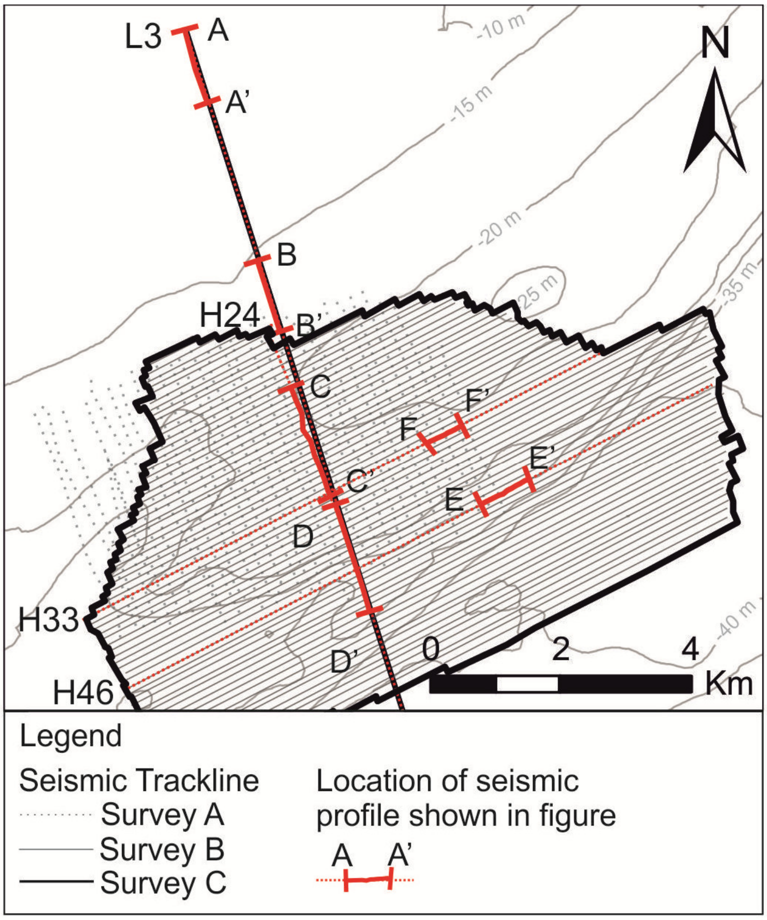


Figure 4.3: Trackplot of seismic reflection profiles and the locations of interpreted seismic line sections presented in figures 4.4 to 4.6. Thick black line delimits interpolation grid.

4.3.2 Bathymetric data collection and processing

To determine depths to seabed, multibeam swath bathymetric data were collected simultaneously with reflection seismic data during Survey B and Survey C (see section 4.3.1). Full details of bathymetric data collection and processing during Survey B are outlined in Cazenave (2007). A Reson Seabat 8125 multibeam system was used in conjunction with a POS MV precision motion and altitude system to obtain bathymetric soundings during Survey C. Post-processing was carried out using QINSy processing software and relevant corrections and filters were applied including patch test calibration results, removal of outliers with automatic and manual filtering, and post-processing of tidal data. For the purpose of this study, multibeam swath bathymetric data were gridded to 1 m cell size to provide a morphological surface to which all seismic stratigraphic interpolations could be tied. Seazone digital survey bathymetry and digital charted bathymetry (Licence No. 112010.009) were obtained for the eastern English Channel to give a regional perspective of seabed morphology. The data were interpolated using kriging in ArcGIS into a 120 m cell grid size.

4.3.3 Vibrocoring

As part of aggregate prospecting and monitoring surveys, 36 vibrocores tied to seismic lines have been recovered from the Hastings Bank region during surveys in 2003 (RMA vibrocore Fig. 4.2d). The RMA provided data from these surveys in the form of vibrocore logs, photographs and particle size distribution analyses. Targeted positioning of the vibrocores by aggregate companies has led to an irregular distribution of cores, with limited data availability in the central region due to dredging activities. Positioning accuracy is within 2 m of the recorded coordinates. Analysis of vibrocore records has enabled the classification and identification of a number of key lithofacies, however given the geotechnical nature of the reports, any small-scale sedimentological details that are vital for interpreting depositional setting were not recorded. An additional six vibrocores were collected during March 2010 to supplement existing vibrocore records, to ground-truth lithofacies to seismic facies, and to provide material for sedimentological analysis (vibrocore sample location Fig. 4.2d). The cores were collected using a high-powered C-CoreHP vibrocorer and recovered in 85 mm-diameter opaque plastic liners. Maximum penetration of the vibrocorer was 5 m, with a maximum recovery of 2.70 m. Cores were immediately sealed and transported to the laboratory where they were split, logged, photographed and sampled. Lithological data collected from each vibrocore dataset forms the basis of lithostratigraphical analysis and allows differentiation of depositional environments.

4.4 RESULTS AND INTERPRETATION

4.4.1 Seismic stratigraphy

Analysis of seismic-reflection profiles has permitted identification of eight seismic units (SU's). The SU's comprise fourteen seismic facies that have been defined based on their external geometry, bounding surface relationships and acoustic properties (Table 4.1). The stratigraphic relationships of the SU's have been resolved using cross-cutting relationships, and are discussed in chronological order, from oldest to youngest. The nature and stratigraphic relationship between individual SU's is demonstrated on interpreted seismic line sections in Figures 4.3 to 4.6. The 3D geometry of SU's BR, A, B, C and D is presented in Fig. 4.7. All other SU's are located outside of the interpolated grid, making it difficult to map their 3D geometry. The oldest seismic unit, SU Br, will be addressed initially in this section and for the remainder of this paper it will be considered as the basement upon which all other SU's are deposited. Integration of remaining SU's with lithological information from vibrocores is presented in Section 4.4.3.

SU Br

SU Br is observed in all seismic profiles and typically forms the base of all overlying seismic units. The base of the unit is masked by seabed multiple reflections and can be observed to a maximum thickness of 40 ms TWTT (ca. 34 m). Truncation of bedding and tectonic structures (normal faults and open folds) at the unit's upper boundary creates a regionally extensive, gently undulating unconformity that is diagnostic of the upper surface of this unit.

Mapping of the upper SU Br surface (Fig. 4.7a) reveals a gently dipping (<0.5°) south-facing planar slope that steepens abruptly (typically to 2-6°) at a SWW-NE-trending recurved break in slope, in present-day water depths of ca. –28 m OD. A second break in slope that trends SW-NE in the study area at ca. -40 m OD defines the north-easternmost margin of the Northern Palaeovalley. The platform is dissected in the northeast by two linear channelised incisions that become confluent to form a NW-SE-trending channel (herein referred to as the Hastings Palaeovalley) that can be traced southwards into the Northern Palaeovalley. A change in slope gradient is expressed through deepening of the channel southward of the Northern Palaeovalley margin. Seismic lines that run perpendicular to the channels show steep sided (>20 m) and symmetrical incision surfaces landward (NW) of the knickpoint and shallower (<10 m), asymmetric incisions seawards (SE) of the knickpoint. The overlying seismic facies show both concordant and discordant relationships with the incision surface.

SU Br represents Cretaceous bedrock, distinguished by the truncation of tectonic structures on its upper surface. The processes responsible for the formation of the unconformity between the bedrock and overlying unconsolidated deposits are not clear. However, given the planar morphology, with only local channelised incision, either planation during lowered sea level and/or wave ravinement during relative sea-level rise are probably responsible.

SU PV

SU PV is observed in line L3 at the northernmost extent of the study area (Fig. 4.4. A-A'). The unit incises deeply into SU Br to a maximum depth of 20 ms TWTT (ca. 17 m) below the present-day seabed; the spatial extent and orientation of incision cannot be constrained using this dataset. The incision surface is irregular (Fig. 4.4 A-A') with a number of troughs preserved ranging in width from 150-300 m. Seismic facies Tf (d) (Table 4.1) infills the topography created by incision and wavy parallel reflectors lap onto the lower bounding surface. Poor acoustic responses prevent any detailed interpretation. However, discontinuous higher amplitude reflectors indicate a complicated multi-storey fill. Reflectors are truncated at the upper bounding surface by overlying seismic units.

SU A

SU A rests unconformably on SU Br and is made up of seismic facies Sh (a), Sh (b) and Ln (b) (Fig. 4.4 B-B'). The unit forms an extensive wedge of sediment that thickens from a minimum of 1 ms TWTT (ca. 1 m) in the west to a maximum of 23 ms TWTT (ca. 20 m) in the east. Downlap of oblique reflectors (apparent dip 1-4°) that diverge onto the lower bounding surface is observed. An unconformity separates two packages of downlapping oblique reflectors towards the north-western region of the study area. Isolated lenses of sediment with sigmoid internal reflection configurations are observed and they appear to exploit topographic lows within the basal surface. The upper bounding surface has truncated reflector terminations below and toplap reflector terminations above.

Seismic Facies	Geometry	Reflector Characteristics
***SU PV* -** Truncation at upper boundary, onlap onto lower boundary		
Tf (d)	Trough fill	Wavy parallel, discontinuous, moderate amplitude, moderate frequency
***SU A* -** Truncation and toplap at upper boundary, downlap onto lower boundary		
Sh (a)	Sheet	Sub-parallel to chaotic, discontinuous, low amplitude, moderate frequency
Sh (b)	Sheet	Oblique divergent parallel, continuous, low amplitude, moderate frequency
Ln (b)	Lens	Sigmoid, continuous to discontinuous, high amplitude, moderate frequency
SU B - Truncation, toplap and concordance at upper boundary, downlap onto lower boundary		
Bn (a)	Bank	Complex convex oblique parallel, continuous, high amplitude, high frequency
Ln (b)	Lens	Sigmoid, continuous to discontinuous, high amplitude, moderate frequency
SU C - Truncation and toplap at upper boundary, onlap and downlap onto lower boundary		
Bn (b)	Bank	Wavy parallel, discontinuous, low amplitude, moderate frequency
Tf (c)	Trough fill	Oblique parallel, discontinuous, low amplitude, low frequency
Tf (u)	Trough fill	Undifferentiated, low amplitude
***SU D* -** Truncation and toplap at upper boundary, downlap and concordance at lower boundary		
Ln (b)	Lens	Sigmoid, continuous to discontinuous, high amplitude, moderate frequency
Tf (a)	Trough fill	Oblique divergent parallel, continuous to discontinuous, high amplitude, high frequency
Tf (b)	Trough fill	Clinoformal, continuous, high amplitude, moderate frequency
Tf (c)	Trough fill	Oblique parallel, discontinuous, low amplitude, low frequency
SU E - Truncation, convergence and concordance at upper boundary, onlap, convergence and concordance at lower boundary		
Ln (c)	Lens	Parallel slightly draped, continuous to discontinuous, moderate amplitude, moderate frequency
Ln (b)	Lens	Sigmoid, continuous to discontinuous, high amplitude, moderate frequency
SU F - Truncation and toplap at upper boundary, downlap onto lower boundary		
Tf (a)	Trough fill	Oblique divergent parallel, continuous to discontinuous, high amplitude, high frequency
Tf (b)	Trough fill	Clinoformal, continuous, high amplitude, moderate frequency
SU G - Reflector terminations unknown		
Sh(u)	Sheet	Undifferentiated, reflectors below resolution of unit thickness
***SU H* -** Toplap at upper boundary, onlap and downlap onto lower boundary		
Ln (a)	Lens	Oblique parallel, discontinuous, low amplitude, low frequency
Ln (u)	Lens	Chaotic, discontinuous, hyperbola diffractions, low amplitude, low frequency

Table 4.1. Summary of seismic facies and seismic units (SU's) interpreted from cross-cutting seismic reflection profiles.

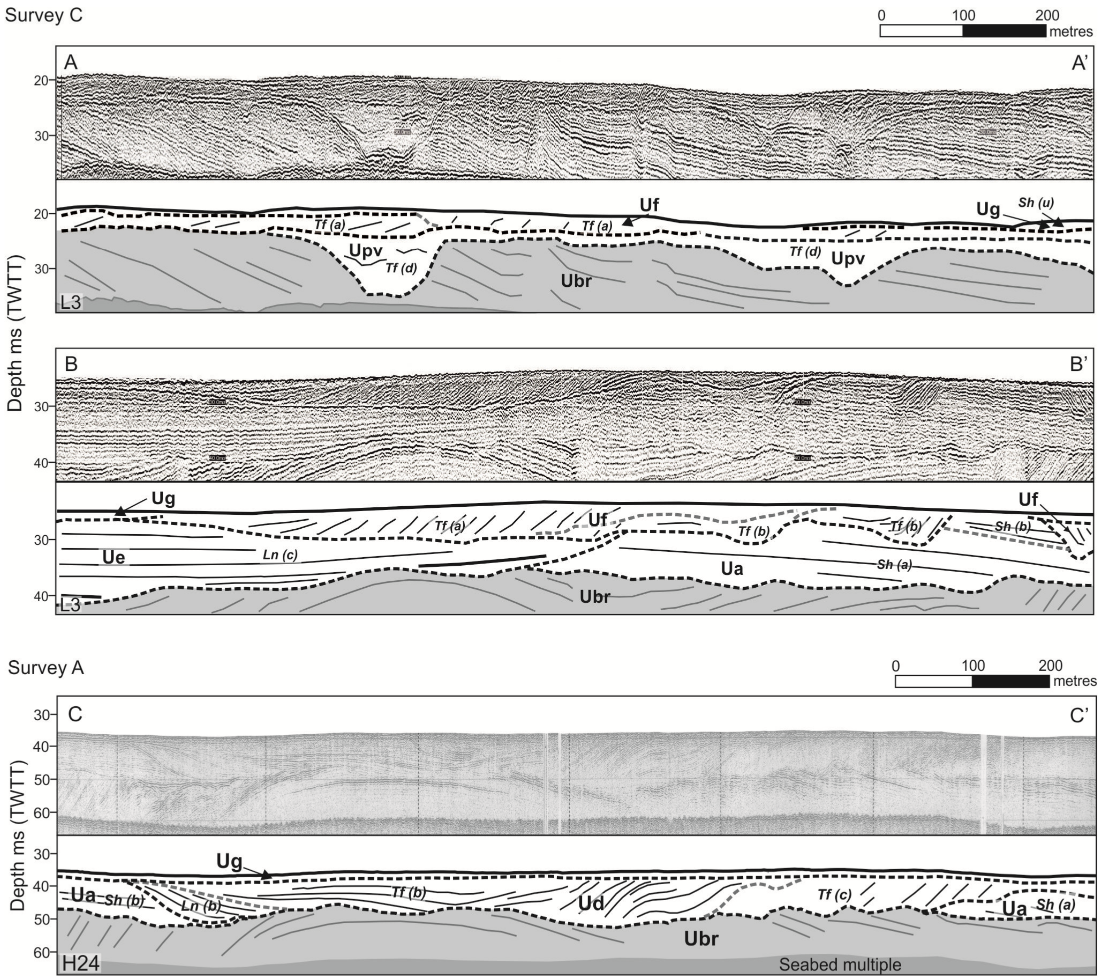


Figure. 4.4: Seismic reflection profiles illustrating seismic facies reflector configurations, the geometry of seismic units (SU's) and the stratigraphic relationship between SU's and the bounding surfaces that separate them. The seismic data are presented in the upper panel and an interpreted section shown below. The grey dashed line separates sesimic facies; the black dashed line separates seismic units and the thin solid black line shows internal reflector configurations. The seabed is represented by a thick solid black line. The location of seismic sections are given in Fig. 4.3.

SU B

SU B is present at the southernmost reach of the study area as an elongate belt that trends in a SW to NE direction parallel to the present-day coastline (Fig. 4.7b). The unit is approximately 6.5 km in length, 0.8 km wide and up to 20 ms TWTT (ca. 17 m) thick. Seismic facies Bn (a) and Ln (b) (Table 4.1) characterise the unit. The basal surface of the unit is erosional and incises into SU A and SU Br (Fig. 4.5). Characteristic aggradational convex-upward reflectors mark a crestline between NW- and SE-stepping oblique parallel reflectors that downlap onto the lower bounding surface. Toplap and truncation are recorded at the upper bounding surface until reflectors become concordant with the bank margin, the position of which has been regionally mapped and corresponds to a break in slope recorded in the upper surface of SU Br. Mapping of the crestline (Fig. 4.7b) indicates that the facies belt comprises two recurved SW-NE-trending sediment bodies. A seismic facies transition from Bn (a) to Ln (a) is observed at the north-easternmost extent of the seismic unit.

SU C

SU C infills the N-S-trending channel feature (Hastings Palaeovalley) that incises into SU Br (Fig. 4.7b). The unit is at its thickest within the channel and can be mapped to a maximum depth of 20 ms TWTT (ca. 17 m) where it becomes obscured by seabed multiple reflectors (Fig. 4.6 F-F'). Seismic facies Tf (u), Tf (c) and Bn (b) (Table 4.1) demonstrate base-discordant relationships with SU Br and SU B. Seismic facies generally exhibit poor acoustic properties and reflector characteristics are difficult to establish. However, toplap and truncation of reflectors are occasionally identified at the upper surface.

SU D

SU D forms an irregular wedge of sediment that thickens from 2 ms TWTT (ca. 2 m) in the west to 15 ms TWTT (ca. 13 m) towards the east (Fig. 4.7b). SU D has a composite seismic signature comprising seismic facies Ln (c), Tf (a), Tf (b) and Tf (c) (Table 4.1 and Fig. 4.4 C-C'). Seismic facies become more complicated towards the NW with increased truncation. The majority of clinoforms dip towards the NW with the exception of isolated areas where reflectors are clinoformal within localised topographic lows. The lower bounding surface incises into SU A and SU C and becomes concordant with SU Br to the NW. Oblique reflectors diverge onto the lower bounding surface and become concordant within topographic lows. Truncation and toplap are observed at the upper bounding surface.

SU E

SU E is less well constrained than other seismic units due to the low spatial resolution of seismic data outside of the interpolation grid. Seismic facies Ln (c) and Ln (b) (Table 4.1) demonstrate discordant lower bounding surfaces that incise into SU A and SU D until they are concordant with SU Br (Fig. 4.4 B-B'). Truncation and concordance of reflectors at the upper bounding surface is observed. The unit can be mapped to a maximum thickness of 20 ms TWTT (ca. 17 m).

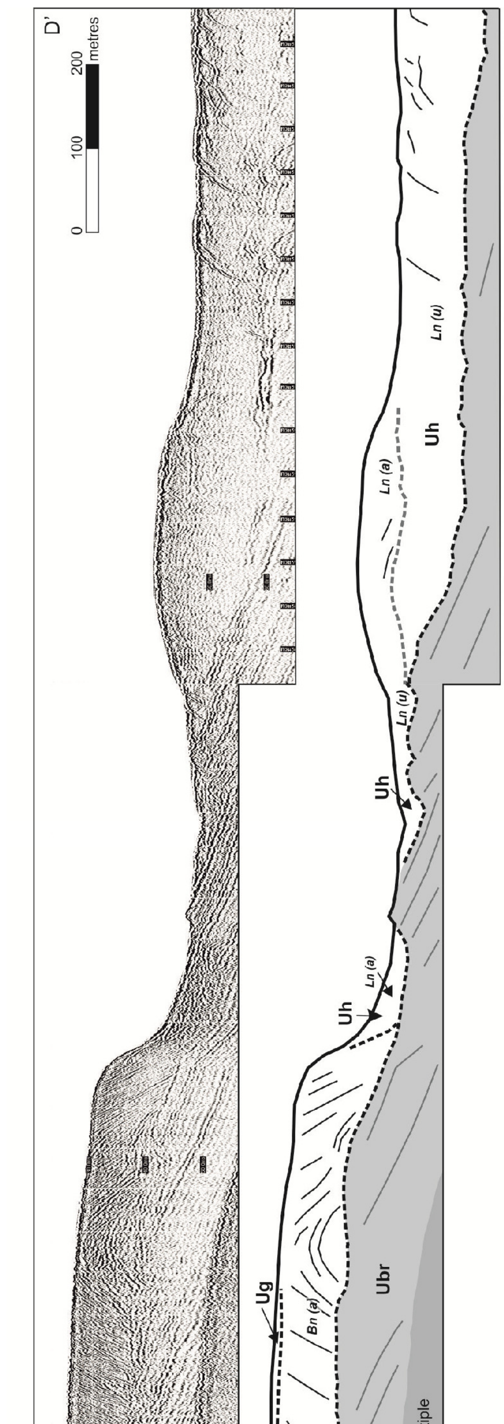


Figure 4.5: See caption for Fig. 4.4.

SU F

SU F can be traced to the north of the area studied, but low spatial resolution of the data set restricts 3D mapping of the unit. SU F comprises a number of eroisonal troughs with irregular lower bounding surfaces that incise into SU A and SU E (Fig. 4.4 B-B'). Oblique divergent parallel and complex sigmoid reflectors downlap onto the lower bounding surface with a dip direction towards the NW. The upper bounding surface is characterised by truncation and toplap reflector terminations. The seismic facies occasionally stack on top of one another to form a succession of up to 10 ms TWTT (ca. 9 m) in thickness.

SU G

SU G can be recognised in all seismic profiles as a thin sheet characterised by seismic facies Sh (u) (Table 4.1). The lower bounding surface truncates underlying seismic units and the upper bounding surface is coincident with the present-day seabed. Typically, the thickness of the unit is below the resolution of the seismic profile and the unit can only be mapped where it exceeds 1 ms TWTT (ca. 1 m). A maximum thickness of 2 ms TWTT (ca. 2 m) has been observed making internal reflector configurations and terminations difficult to establish.

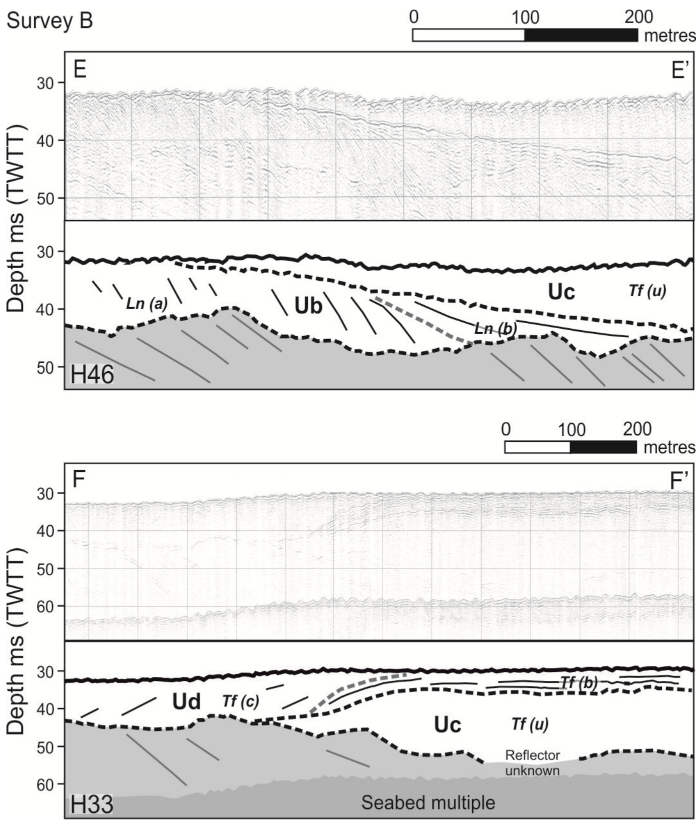


Figure 4.6: See caption for Fig. 4.4.

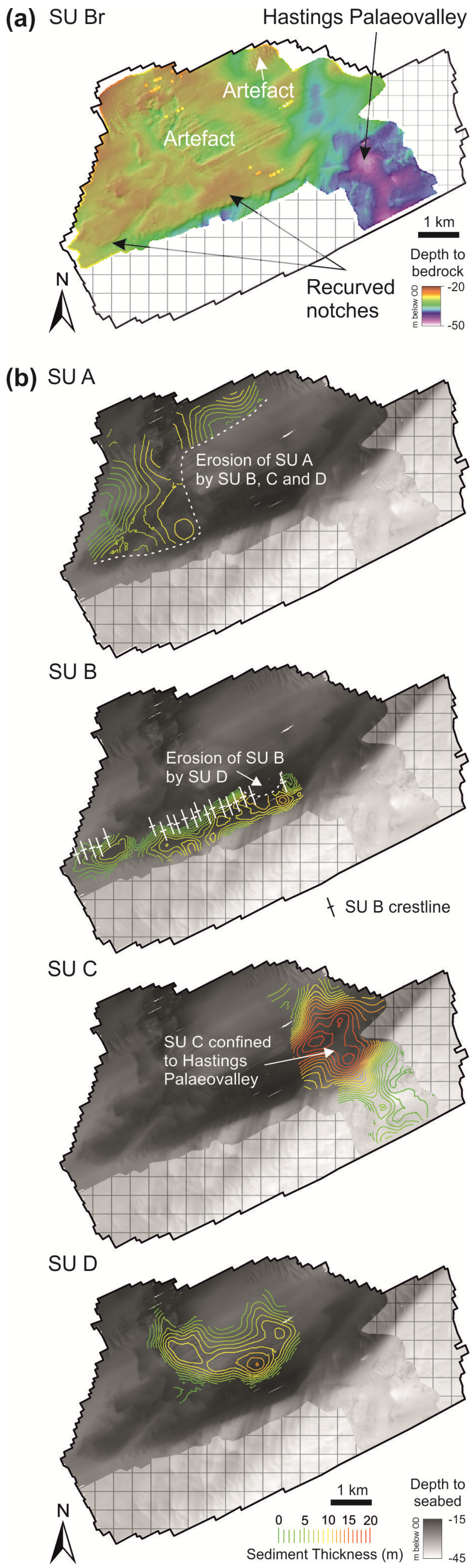


Figure 4.7: (a) Morphology of bedrock surface (SU Br), calculated by subtracting sediment thickness (m) from bathymetric model (m OD). Artefacts occur when features of the bathymetric surface (ie. sediment waves) are smaller than the resolution of the sediment thickness surface and through the interpolation process are misrepresented on the resultant surface. Areas of no data are represented by cross hatching. (b) Contoured isopachs of sediment thickness overlying seabed bathymetry (© British Crown and SeaZone Solutions Limited. All rights reserved. Product license No. 112010.009) highlighting 3D geometry of SU's A, B, C and D. Areas of no data are represented by cross hatching. For all images, sediment thickness converted from time to thickness using an acoustic velocity of 1700 ms^{-1}.

SU H

SU H forms a discontinuous wedge of sediment present in the southernmost reaches of the area studied that varies in thickness from 1 ms TWTT (ca. 1 m) to 15 ms TWTT (ca. 13 m) (Fig. 4.5). The unit rests above SU Br, and in places laps onto the southern margin of SU B. Seismic facies Ln (u) exhibits a chaotic internal reflector configuration with hyperbola diffractions at the upper bounding surface. Occasional oblique reflectors exhibiting toplap at the upper bounding surface and downlap onto an irregular lower bounding surface (seismic facies Ln (a)) are observed.

4.4.2 Lithofacies

Five key lithofacies have been identified based on sedimentary structure, grain-size, composition, texture and fossil content (Fig. 4.8). Targeted positioning of the vibrocores by the aggregate companies has led to a bias towards coarser grained sediments. Cores penetrated SU's A, B, D, E, F and G. Lithofacies codes have been adopted from Evans and Benn (2004).

Lithofacies Sh: bedded gravelly sand

Lithofacies Sh is moderately to well sorted, medium to very coarse, horizontally bedded sand. A minor fine to medium gravel component composed of angular to sub-rounded clasts of flint, quartzite and sandstone that are distributed randomly throughout the sand. Organic material and Fe mottles are occasionally present and fragmented marine shells (typically <2 mm) are frequent throughout (~15% of total sample).

Lithofacies Sl: fine to medium sand with horizontal and draped mud laminae

Lithofacies Sl is characterised by well sorted, fine to medium grained, occasionally finely laminated sand with mud laminae, up to 1 cm in thickness, that drape beds. Heavy mineral detritus is occasionally seen. Fragments of thin-walled shell are present (typically <0.5% of sample) of fine to medium grained sand size.

Lithofacies Sfp: interbedded laminated fine sand and mud

Lithofacies Sfp represents interbedding of laminated fine sand with laminated mud beds of up to 5 cm thickness. Horizontal to inclined bedding structures are preserved with rare trough cross-bedding.

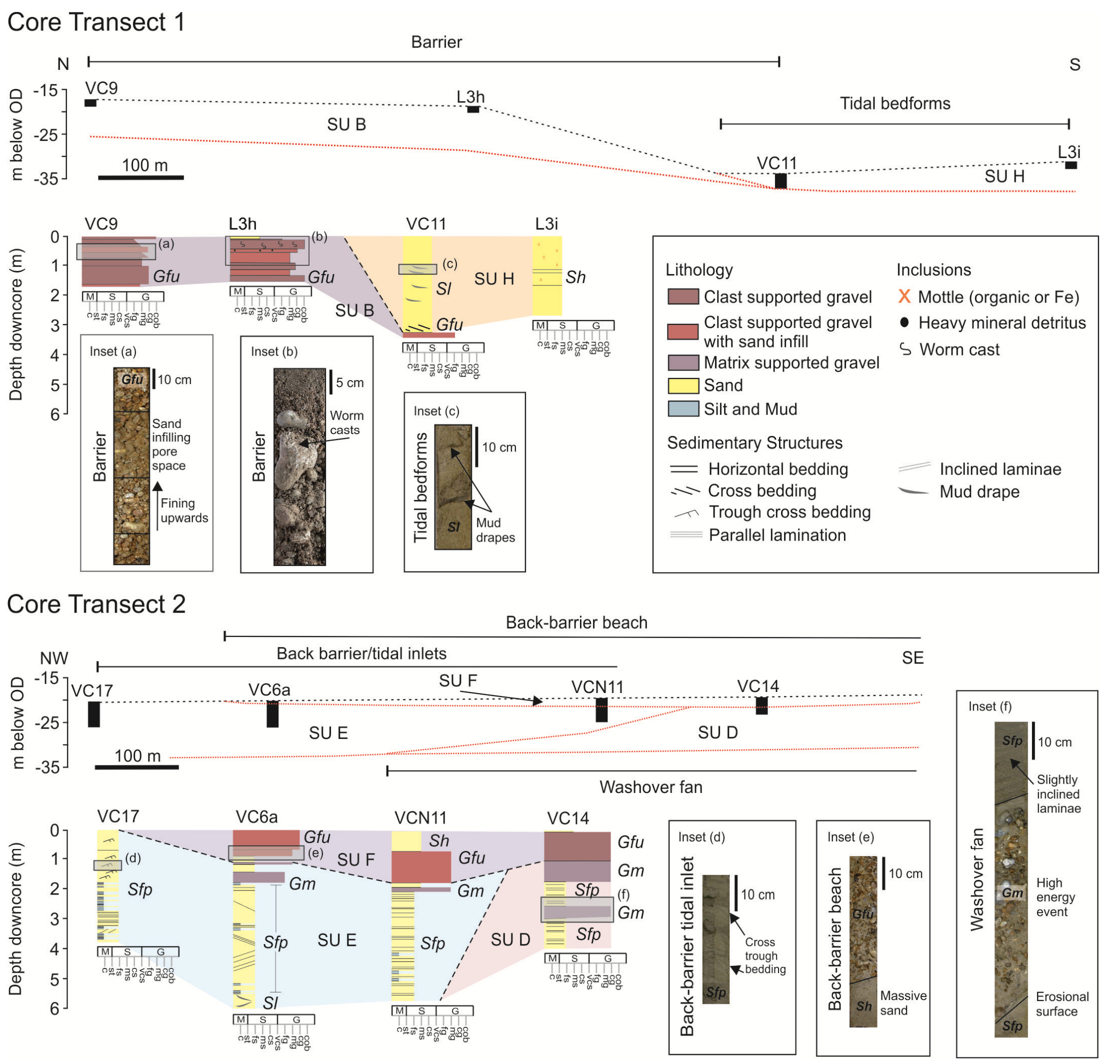


Figure 4.8: Lithofacies and lithostratigraphic correlation to seismic units. Location of core transects shown on Fig. 4.1(d).

Lithofacies Gfu: clast-supported gravel

Lithofacies Gfu is characterised by moderately to poorly sorted clast-supported gravels that exhibit weak normal grading (10-60 cm bed thickness) with abrupt to gradational boundaries. Gravel clasts vary in size from fine gravel to cobble and are angular to sub-rounded depending on lithology. Flint, quartzite and sandstone dominate, with less frequent occurrences of granite and schist clasts. The gravel fabric is open and core samples comprise up to 91% gravel content. Locally, the gravel fabric is loosely infilled with a fine to coarse sand matrix and occasional interbedding of sand lenses is observed. Fragmented shell material of <2 mm diameter is recorded and typically accounts for <1% of the samples analysed from cores.

Lithofacies Gm: matrix-supported gravel

Lithofacies Gm comprises poorly sorted, matrix-supported gravel. The gravel component is fine gravel to cobble size, angular to sub-rounded clasts of predominantly flint, quartzite and sandstone with occasional lithics (granite and schist). The matrix consists of fine to medium sand with a typical fabric to matrix ratio of 3:2. Shell fragments of sand to fine gravel size are present and form shell-rich beds within the upper 30 cm of some cores.

4.4.3 Depositional environments

Mapping and interpretation of seismic stratigraphic units provides information on sedimentary processes, environmental setting and depositional energy within a system (Mitchum et al., 1977). Calibration of seismic stratigraphic units with lithological information from vibrocores can reinforce interpretations and permit a more comprehensive reconstruction of landscape evolution and palaeoenvironments. Nine depositional units (DU) have been identified by establishing relationships between seismic stratigraphic units and lithofacies as outlined in Table 4.2 and Fig. 4.9. The units are presented in chronological order (oldest to youngest) and will be discussed in terms of their interpreted environment of deposition.

Depositional Unit	**Seismic Unit**	**Lithofacies**	**Interpretation**
-	SU Br	No data	Bedrock
DU I	SU PV	No data	Fluvial channel-fill
DU II	SU A	Sh	Shoreface
DU III	SU B	Gfu	Barrier (barrier shore and back-barrier beach)
DU IV	SU C	No data	Infilled palaeovalley (Hastings Palaeovalley)
DU V	SU D	Gm, Sfp	Washover fan
DU VI	SU E	Sfp, Gm	Back-barrier tidal inlet
DU VII	SU F	Gfu	Back-barrier beach
DU VIII	SU G	Sh	Small bedforms
DU IX	SU H	Sl, Sh	Large tidal bedforms

Table 4.2: Summary of depositional units and associated environmental interpretation established through correlation of seismic units and lithofacies.

DU I: fluvial Channel-fill

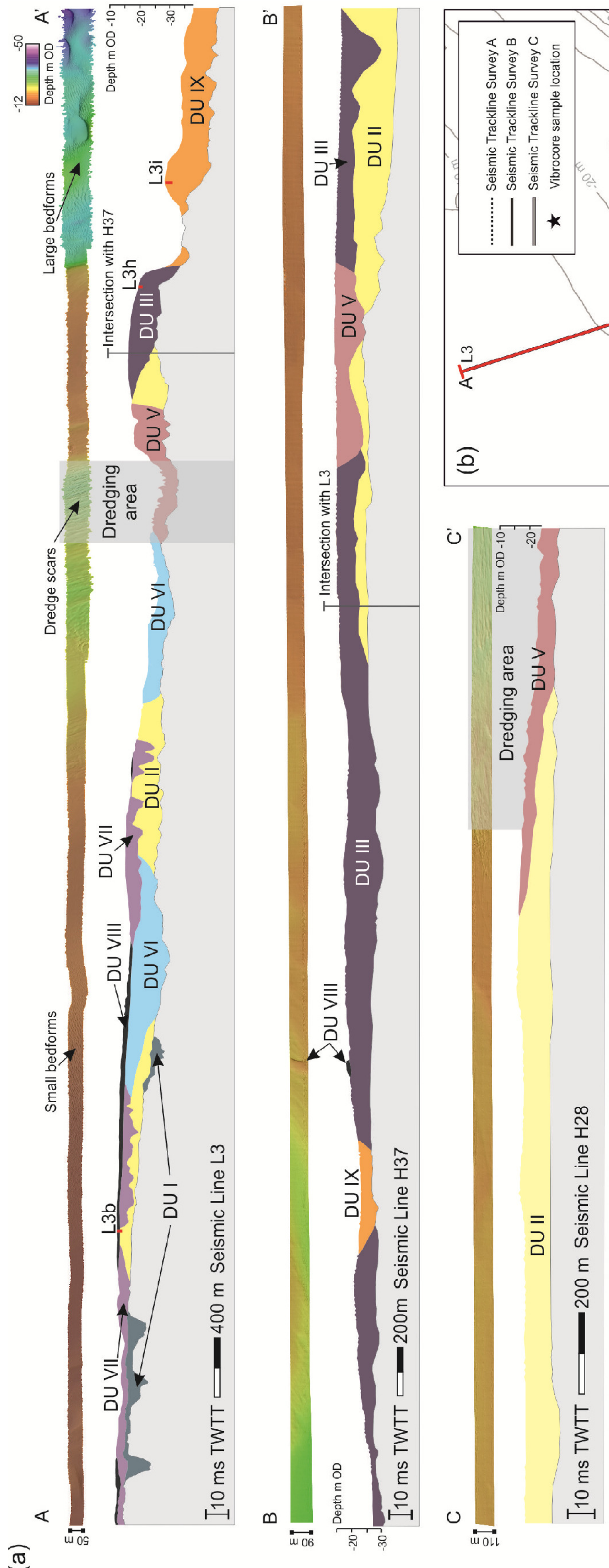
DU I is restricted to the northern reaches of the area studied and no information on lithology is available from vibrocores. The irregular concave-upward geometry of the lower bounding surface is thought to have formed through fluvial incision into the underlying bedrock. The nature of processes responsible for infilling the channel are unclear. Wavy parallel seismic reflectors imply vertical accretion in relatively low energy environments. Multi-storey fill, bounded by erosional surfaces, does not allow for discrimination between deposition under fluvial and tidal channel regimes. Further, it is not possible to establish a direct link with the Hastings Palaeovalley given the constraints of this dataset, however the presence of a knickpoint down dip of the Hastings Palaeovalley suggests it formed as part of a larger fluvial drainage network.

DU II: shoreface

DU II comprises SU A and lithofacies Sh. The unit forms an extensive sheet of sand considered to have been deposited in a SE-facing shoreface setting. Apparent dip calculations show steepening of low angle clinoforms from ca. 1° to ca. 3.5° along a NNW-SSE trend. Isolated lenses of sigmoid reflectors record changes in sedimentation rates due to increasing availability of accommodation within topographic depressions, indicating a hiatus between erosion of the underlying bedrock surface and deposition of this unit. Deposition of lithofacies Sh places deposition above fair weather wave base rather than in the offshore environment where highly bioturbated finer grained sediments would be expected (Dashtgard et al. 2010). The mottled texture of lithofacies Sh is a potential indicator of post-depositional oxidation resulting from bioturbation. The presence of gravel, detrital heavy minerals and foraminifera (e.g. *Elphidium sp.*) indicative of inner shelf marginal marine environments, within lithofacies Sh places the deposition towards the upper shoreface to foreshore transition.

DU III: barrier

DU III comprises SU B and lithofacies Gfu and forms two recurved ridges of coarse grained, clast-supported gravel interbedded with sand lenses. Convex-upward reflectors are interpreted as the product of aggradation with bidirectional downlapping clinoforms (apparent dip >20°) representing landward (NNW) and seaward (SSE) aggradation. The composition of lithofacies Gfu indicates deposition in an environment capable of transporting clasts of up to cobble size that selectively sort grains depending on their size



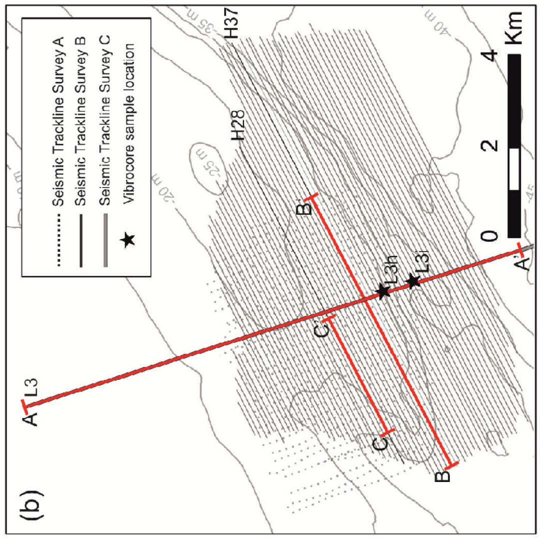


Figure 4.9: (a) Scematic illustration highlighting the stratigraphic relationship between depositional units, as interpreted from seismic reflection profiles calibrated with lithological information from vibrocores. Cores are drawn to scale on the the y axis. Swath bathymetry surveyed during seismic data aquisition shown above each profile. (b) Location of seismic reflection profiles

into normal graded beds (coarse- to fine-gravel). Lithofacies Gfu is considered to exhibit characteristics of deposition in a nearshore beach environment (Orford, 1975; Bluck, 1999; Orford et al., 2002). Where sand infills the gravel fabric and sand lenses are present, periods of fair weather deposition are inferred. An open gravel fabric is considered to represent either (i) degree of winnowing of sand through swash-backwash processes (Hey, 1967) or (ii) deposition of gravel by storm waves.

The geometry and lithological composition of the depositional unit is indicative of formation of gravel beach ridges on a coastal strand-plain, and only through association with DU VI the beach ridges can be classified as a barrier. Alignment of the barrier (using crestline orientation), changes in sediment thickness and the degree of grain sorting between the two individual recurved ridges suggests reworking of sediments alongshore parallel to the present shoreline (towards the NE). Cross-shore variations in grain size and the degree of sorting are a function of the nature of wave break on the coastal profile between storm and inter-storm conditions. Apparent dip of clinoforms steepens seawards of the barrier crestline and marks an overall coarsening of lithofacies Gfu down-dip along the beach profile. A switch in depositional processes towards the east of the study site, characterised by seismic facies Ln (b), marks the position of the Hastings Palaeovalley. Reflector characteristics of seismic facies shows progradation of relatively finer grained sediments into the palaeovalley. No vibrocore samples were retrieved in this area, however interpretation of acoustic backscatter data identifies sediments on the seabed typically of grain sizes between 3-7 mm (Cazenave, 2007). The palaeovalley is thought to create a topographic obstacle preventing migration of the barrier further towards the NE.

DU IV: infilled Palaeovalley (Hastings Palaeovalley)

The lack of vibrocore data in this area combined with the spatial resolution of seismic lines limits the interpretation of DU IV. The concave-upward geometry of the lower erosional bounding surface is interpreted as the base of a bedrock valley considered to have formed through fluvial incision. Given the stratigraphic position of this depositional unit, a hiatus between incision and deposition is inferred. Deposition within the valley is complicated and difficult to establish given the low-amplitude nature of reflectors. Oblique, parallel and wavy parallel reflectors represent both progradation and aggradation, and possible lateral accretion, of sediment bodies within the valley. These reflector configurations may represent interactions between fluvial, tidal and wave regimes as the pre-existing fluvial valley was inundated during relative sea-level rise (Chaumillon et al., 2010). Low amplitude and low frequency reflectors suggest valley infill is fine grained (probably sand) and given the proximity of the palaeovalley to the shoreline, deposition is considered to have occurred predominantly under the influence of tides in an open estuarine setting.

DU V: washover fan

DU V has been interpreted as a washover fan formed through breaching of the barrier (DU III). Seismic facies suggest overall progradation in a NW (landward) direction with alternating up-building and deposition bypass within a high energy regime. Landward thinning of the deposit with increased erosional truncation at the seaward margin is typical of a washover fan created by storm surges (Sedgwick and Davis, 2003). Incision of SU C suggests deposition of the fan subsequent to, or synchronous with, infilling of the Hastings Palaeovalley. The washover fan is thickest (13 m) at the point of breaching of the barrier suggesting sediment was transported from the barrier shore into the back-barrier environment (Fig. 4.1a). Vertical stacking of seismic reflectors implies the washover fan is not the result of a single event but the product of multiple phases of deposition. The morphology of the back-barrier, i.e. a topographic depression associated with the Hastings Palaeovalley (Fig. 4.7a) may have maintained the space available for infilling over multiple depositional events. Limited lithological information is available for this unit. Vibrocores sampled from the head of the washover fan comprise lithofacies Gm that is interpreted to represent deposition by turbulent water in a high energy setting as the barrier is breached by waves. The lithology and composition of the sediment suggests reworking of barrier beach gravels and shoreface sands. Towards the more distal (landward) fan setting, lithofacies Gm and Sfp represent deposition of finer grained laminated fine sands that are interbedded with poorly sorted matrix-supported gravels indicative of a decline in wave influence in a back-barrier setting. These observations support a landward change from a proximal barrier breach to back-barrier setting.

DU VI: back-barrier tidal inlet

Seismic Unit E and lithofacies Sfp and Gm characterise DU VI. The unit extends north beyond the seismic grid. Sigmoid reflectors of seismic facies Ln (b) are thought to represent deposition due to the creation of accommodation by erosion of the underlying shoreface and washover fan sediments. After initial erosion by tidal and/or storm scouring, slightly draped parallel reflectors indicative of even sedimentation rates in a low energy setting are recorded. Deposition of fine-grained sands intercalated with mud laminae suggests deposition under variable energy regimes. DU VI is interpreted to represent deposition landward of a barrier inlet fed by the Hastings Palaeovalley to the east. Isolated beds of lithofacies Gm shows extension and interfingering of the washover fan into the back-barrier during periods of increased storminess. The lack of organic sediments indicates the back-barrier was open to tidal flushing during deposition of DU VI. The full extent of the back-barrier is difficult to map and a fluvial influence cannot be established.

DU VII: back-barrier beach

DU VII has a similar seismic and lithological signature as the foreshore deposits characteristic of DU III. Landward-stepping (NNW), oblique clinoformal and divergent reflectors suggest gradual infilling of asymmetric erosional scours. The 3D geometry of these sediment bodies is unknown, however taken in the context of other depositional units they are thought to represent landward migration and rollover of barrier beach ridges. The presence of lithofacies Gfu, previously interpreted as representing deposition in a nearshore beach environment, supports this hypothesis. DU VII is, therefore, interpreted as the back-barrier shoreline of the barrier.

DU VIII: small bedforms

DU VIII cannot always be observed in seismic profiles as the basal surface and internal reflector configurations are typically below resolution of the seismic pulse. DU VIII is not always represented in vibrocores. Locally, however, <0.3 m thicknesses of lithofacies Sh have been observed and a higher sand fraction within the gravelly sediments is recorded. The planar nature of the lower bounding surface is interpreted as a wave ravinement surface, with thin overlying deposits representing flooding of the shoreline during relative sea-level rise. Sedimentary processes operating subsequent to wave ravinement are likely to be influenced by tidal and wave regimes operating in initially shallow waters.

DU IX: large tidal bedforms

Depositional unit IX is present south of the Hastings Bank margin. Two vibrocores have been recovered from this area that show lithofacies Sh and lithofacies Sl. Discontinuous low amplitude oblique downlapping reflectors stem from progradation of the unit towards the NE. The morphology of the upper bounding surface is recorded on the seabed as a series of N-S-trending elongate ridges that are asymmetric in profile from W-E (Fig. 4.5). Based solely on their morphology, the ridges have been interpreted as bedforms deposited by long-term sediment transport (weeks to years) under a tidal regime (Cazenave, 2007). Fine sands interbedded with mud laminae and mud drapes are indicative of deposition under the influence of tides (Dashtgard et al., 2010). An erosional surface separates seismic facies within the depositional unit and is related to reworking of the upper 10 m of sediments. This is thought to represent migration of smaller bedforms over remnant deposits due to changes in sediment supply and/or tidal prism**.** The seismic signature and lithology established during this study supports the interpretation of Cazenave (2007) that deposition was the result of subtidal currents transporting sediment along the bank margin after-submergence.

4.4.4 Age assessment

The timing of deposition at Hastings Bank is currently unknown due to the lack of chronometric data for sediments in this area. However, an estimate of age can be established by comparing the available relative sea-level data, which is well constrained for the south coast of Britain during the Holocene (Waller and Long, 2010), to the reconstructed elevation of landforms relative to mean sea-level (MSL). This analysis assumes minor erosion/reworking of landforms post submergence so that the preserved morphology is that of the landform at the time of formation. Given the erosional nature of most depositional environments presented in this paper this assessment can only be confidently applied to the barrier (DU III). Using Dungeness foreland as a modern analogue (Plater and Long, 1995), mean sea-level is expected to be ca. 5 m below barrier crest height. By establishing the average crest height of the barrier preserved at Hastings Bank, and incorporating an uncertainty on this elevation of ± 1 m that covers the range of crest heights observed, an elevation relative to MSL can be determined (Fig. 4.10). Assuming the barrier is breached between MSL and MSL + mean high water (MHW) + significant wave height (H_s), the average elevation of the barrier in front of the washover fan (DU V) provides a timeframe for breaching of the barrier (DU III) (Fig. 4.10). According to the data presented in Fig. 4.10, the barrier was active during the early Holocene and was in existence between ca. 9.5 ka and 8.8 ka, and was breached between ca. 9.2 ka and 8.3 ka. This indicates an early Holocene age and provides a relative chronology in the form of a temporal benchmark for the depositional history of other environments interpreted within the barrier/back-barrier complex.

4.4.5 Landscape evolution

A conceptual model to explain landscape evolution at Hastings Bank has been developed that considers the relationship between depositional units and the nature of bounding surfaces that separate them. Six phases of landscape evolution (LE Phase) are proposed and are summarised on Fig. 4.11. The landscape evolution model is based on a relative sequence of events and constrained by the age estimates established in section 4.4.4.

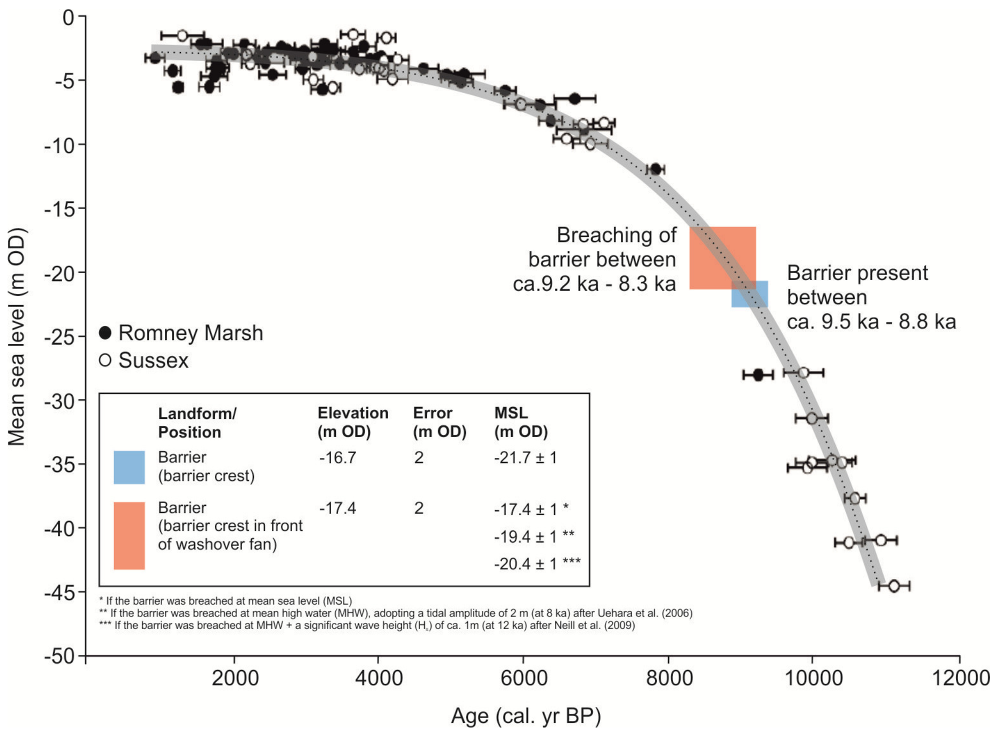


Figure 4.10: Timing of barrier presence and breach, extrapolated according to landform elevation and relative sea-level history. Plot of sea-level index points for south-east Britain reproduced after Waller and Long (2010). A line of best fit (black dashed line) including 1 sigma error (grey transparent line) was qualitatively fitted to the data points to allow interpolation within areas of no data.

LE Phase 1: fluvial incision of a lowland plain

The continental shelf emerges in response to glacio-eustatic sea-level fall revealing a relatively flat, lowland plain. Cold climate conditions prevail and vegetation cover is considered to be sparse. Soils are poorly developed and in places bedrock is sub-aerially exposed. Rivers drain the relatively high relief created by the South Downs and extend across the exposed continental shelf, incising bedrock channels along their path (DU I section 4.4.3). On the SE coast of England offshore extensions of the rivers Ouse, Cuckmere, Adur and Arun have been recognised (Smith, 1989). Given the location of Hastings Bank in comparison to present-day river catchments, the Hastings Palaeovalley may be part of an early Combe Haven drainage network (Fig. 4.1a). According to the elevation of the bedrock platform upon which Hastings Bank is built (Fig. 4.7a), a minimum relative sea-level of –30 m OD is required to enable fluvial incision making this phase of landscape evolution older than 10 ka (Fig. 4.10).

LE Phase 2: transgression and barrier initiation

During rapid early Holocene relative sea-level rise the continental shelf is flooded. Widespread marine planation associated with transgression erodes existing sediments and the underlying Cretaceous strata (mudstone, sandstone and chalk). A shoreface begins to prograde towards the southeast (DU II) supplied by sediment entrained and rolled forward during transgression. As the shoreface builds and water depths decrease locally, the influence of waves increases and alongshore reworking of sediments takes place (Fig. 4.11). In this shallow-water environment, flint-rich gravel is deposited in the nearshore under the influence of waves and storms forming a collection of (gravelly) recurved beach ridges (DU III) (Fig. 4.6a) that are superimposed upon a sandy shoreface. Alongshore and offshore migration of the shoreline is limited by the presence of the Hastings Palaeovalley and Northern Palaeovalley, respectively (Fig. 4.11). The barrier is present and spatially stable between 9.5 ka and 8.8 ka.

LE Phase 3: sediment recycling and breaching of the barrier

The barrier enters a phase of breakdown. This may be linked to a reduced sediment supply whereby continued alongshore sediment transport can only be achieved through recycling of the up-drift barrier. Alongshore progradation of sediment starts to infill the Hastings Palaeovalley (DU IV) (Fig. 4.11). Beach ridges are reworked and breached creating tidal inlets and associated back-barrier tidal environments (DU VI). Some gravel ridges become disconnected from the coastline to form offshore barrier islands (DU III). The influence of waves remains strong and the ‘barrier island’ environment is breached, resulting in the transport of sediment into the back-barrier to form a washover fan (DU V). Breaching occurs between 9.2 ka and 8.3 ka (Fig. 4.10). Assuming deposition of the shoreface began at 10 ka when marine waters started to encroach the bedrock platform at -30 m OD, a maximum timeframe of barrier existence prior to breaching would be 1.2 ka.

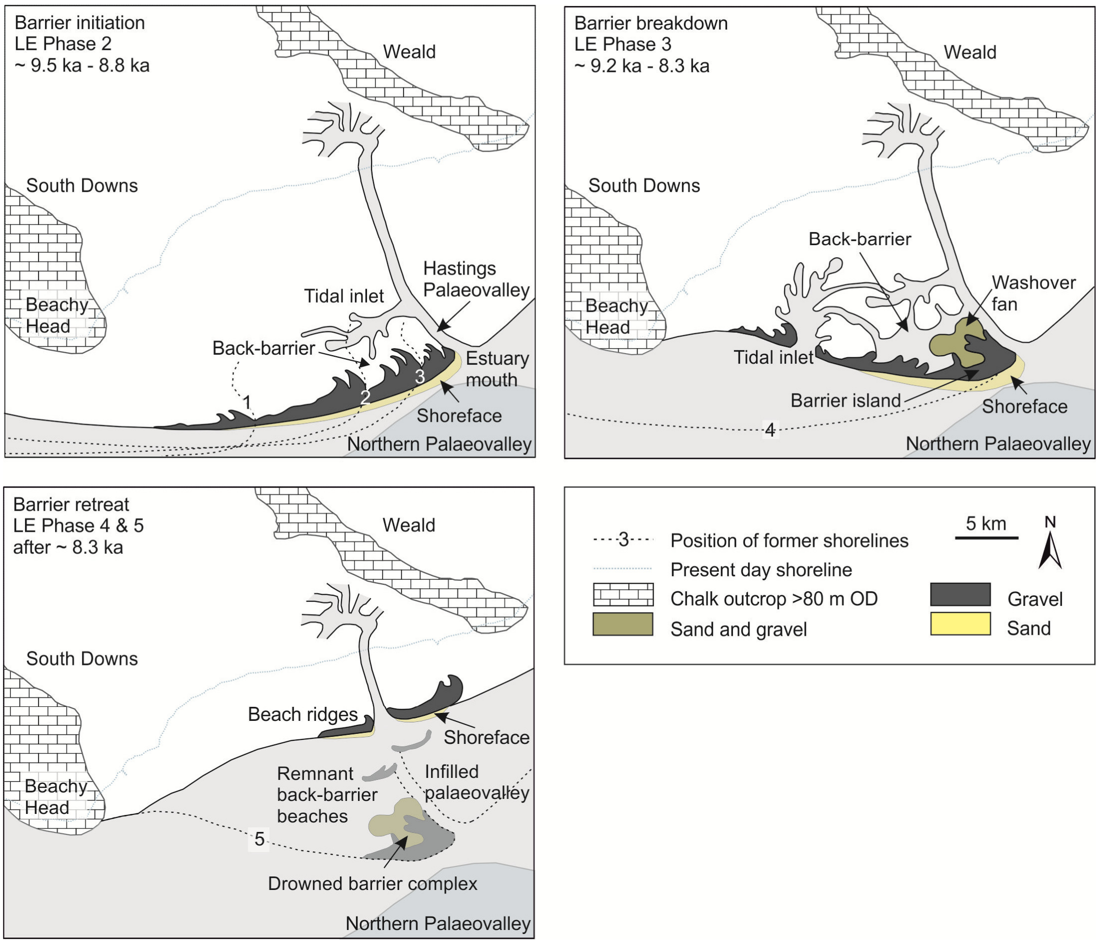


Figure 4.11: Conceptual model outlining evolution of the barrier complex in response to sea-level transgression, interpreted from the geometry and stratigraphy of depositional units. Dashed lines and numbers represent position of former shorelines, evolutionary stages shown in chronological order from 1 to 6. LE Phases refer to landscape evolution phase, see section 4.4.5 in main text for full details.

LE Phase 4: drowning of the barrier and landward migration of the shoreline

Relative sea-level continues to rise and the degraded barrier complex is drowned without reworking of the seaward face, i.e. barrier overstepping. The capacity for the barrier to adjust to this continued drowning through landward migration is exceeded and it becomes stranded offshore (Fig. 4.11). This phase of landscape evolution is expected to have occurred after 8.3 ka (Fig. 4.10).

LE Phase 5: landward migration of the shoreline through overstepping

Relative sea-level rise continues and the shoreline migrates landwards. As the shoreline retreats, gravel beach ridges within the advancing surf zone migrate in step (rollover) creating an erosion surface. Shoreline retreat is discontinuous and episodic overstepping leads to preservation of isolated remnants of back-barrier beach deposits (DU VII) offshore of the advancing shoreline (Fig. 4.11).

LE Phase 6: highstand

Relative sea-level stabilizes around its present level and the continental shelf is fully submerged. Seabed sedimentation is limited. Finer grained deposits at the coast are remobilised and deposited offshore of the bank margin in deeper water depths due to tidal currents, forming a range of sandy bedforms (ripples, waves and banks). Assuming coastal and nearshore hydrodynamics have been similar to the present day since reconnection of Atlantic waters with the southern North Sea at ca. 8 ka ago (Shennan et al., 2000), Hastings Bank is at depths which have been beyond the influence of waves and tides since ca. 7 ka.

4.5 DISCUSSION

Volumetrically, the most significant phases of deposition at Hastings Bank are represented by the coastal and shallow marine facies of the barrier complex. Deposits preserved at Hastings Bank record phases of barrier initiation, breakdown, retreat and abandonment during early Holocene relative sea-level rise.

4.5.1 Barrier initiation

From the bathymetry, a relative sea-level of ca. –30 m OD is required to switch processes operating at Hastings Bank from terrestrial to coastal and shallow marine conditions. Initial development of the barrier complex would require a sufficient supply of sediment to keep pace with relative sea-level rise. This may have been achieved prior to opening of the Straits of Dover when deposition of sediment transported by waves and tides, in a prevailing north-easterly direction (Uehara et al., 2006; Neill et al., 2009), would have been limited by the palaeogeographical configuration of SE England (Shennan et al. 2000). However, tidal range in the eastern English Channel and thus the ability of tidal currents to transport sediment alongshore, only increased after opening of the Straits of Dover (Uehara et al., 2006). Therefore, the timing of reconnection between Atlantic waters and the southern North Sea though the Straits of Dover may have been crucial in determining initial development of the barrier complex at Hastings Bank.

At the present day, sediment supply to gravel beaches on the south east coast of Britain has been largely determined by erosion and transportation of flint from retreating chalk cliffs and offshore to onshore supply of coarse clastic sediment resulting from terrestrial processes operating on the shelf during cold stage sea-level lowstand periods (Jennings and Smyth, 1990; Anthony, 2002). In the eastern English Channel the availability of sediment for offshore to onshore transport may have been enhanced through erosion during rapid early Holocene transgression as documented in the form of an extensively mapped ravinement surface (Wright, 2004). Where pre-existing sediment cover was thin, erosion of the underlying bedrock (Lower Greensand, Weald Clay and Chalk) may have created an additional sediment source that supplied finer grained sediments to the system. The extension of fluvial valleys offshore during sea-level lowstand created a conduit for transporting coarse grained sediment beyond the shelf edge (Bellamy, 1995), which was reversed during subsequent sea-level rise as some valleys backfilled with thick, fine grained, transgressive deposits (e.g. Velegrakis et al., 1999; Gupta et al., 2004; Wessex Archaeology 2008). Parts of the palaeovalley complex in the eastern English Channel, including the Northern Palaeovalley, are underfilled (Hamblin et al., 1992); here confined tidal currents through these valleys (Uehara et al., 2006) may have facilitated the transport of fine-grained sediment onshore.

The locations of former headlands on the south east coast of Britain is unknown. The chalk cliffs at Beachy Head (Fig. 4.1) are undergoing rapid erosion (Dornbusch et al., 2008; Moses and Robinson, 2011) and their maximum extent offshore during the early Holocene has been estimated at 5 km south of the present-day coastline (Jennings and Smyth, 1990). Erosion of chalk cliffs is important for maintaining supply of flint gravel to the coastline. The relative contribution of sediment from the erosion of cliffs to deposits at Hastings Bank is difficult to quantify. However, limited and discontinuous retreat of cliffs during the Holocene (Jennings and Smyth, 1990) implies that sediment transported from the offshore zone is a more important source during early phases of transgression. Sediment supply to Hastings Bank was maintained during initial development through marine planation and erosion of Cretaceous strata along with reworking of coarse clastic sediments that were stored on the continental shelf during sea-level lowstand.

The bathymetry of the shelf offshore of Hastings Bank is characterised by a relatively deep palaeovalley (Northern Palaeovalley) that abruptly flattens onto a wide plain. During rapid rates of early Holocene sea-level rise (Smith et al., 2011) this considerable change in inclination of the bedrock slope would have created an extensive shallow-water plain at the margin of the palaeovalley allowing shoreface sedimentation to begin. Through increased sedimentation and consequently a reduction in water depth, a threshold was reached that allowed deposition of gravel ridges superimposed upon the shoreface. The Northern Palaeovalley probably played an important role in the spatial development of the barrier by hindering progradation farther offshore into deeper waters, instead encouraging lateral migration of the coastal system along the palaeovalley margin. Alongshore migration can only be maintained without the presence of additional topographic obstacles, and at Hastings Bank this was inhibited by the Hastings Palaeovalley. Initial barrier development at Hastings Bank is characterised by limited seaward and enhanced alongshore migration of a number of recurved ridges that overlie shallow marine facies typical of a prograding barrier system (Roy et al., 1994).

4.5.2 Barrier breakdown

The barrier complex at Hastings Bank records a phase of landscape degradation and sediment reworking. Barrier resilience to morphodynamic change and breakdown operates at different timescales from decades to thousands of years (Long et al. 2006). The time frame of barrier existence at Hastings Bank prior to drowning is >1 ka. At this temporal scale, barrier breakdown results from gradual exhaustion of sediment supply (Orford et al., 1991) and/or enhanced wave activity during relative sea-level rise (Orford et al., 1995). How barriers reorganise in response to these forces depends on the coastal morphology and inherited topography upon which they are built (Fitzgerald and Van Heteren, 1999).

It is not possible to simply attribute reorganisation of the barrier to either a reduction in sediment supply or rising sea levels as transgression advanced. Site-specific inherited topography is considered to play an important role in the degradation of the barrier at Hastings Bank. The Hastings Palaeovalley and associated back-barrier tidal inlets form local sediment sinks, and for sediment supply to keep pace with the rate of infilling, the barrier enters a phase of breakdown and sediment reworking. Reworking of sediment within the barrier complex can result in a shift in barrier alignment from drift-aligned, where sediment is transported alongshore, to swash-aligned where sediment is recycled through the beach ridge parallel to wave approach (Orford et al., 2002). Degradation of barriers and breaching by tidal inlets can introduce a significant cross-shore vector that further interrupts alongshore sediment transport (Fitzgerald and Pendleton, 2002). Landward and seaward transport of sediment shows the barrier at Hastings Bank ultimately developed into a swash-aligned feature that was punctuated by tidal inlets. Morphology and alignment can influence the stability of a barrier with swash-aligned barriers being more susceptible to breaching (Orford et al., 1991) as is observed at Hastings Bank through segmentation of the barrier and the development of a washover fan. Erosion of the back-barrier shoreline through breaching creates additional sinks for sediment, which, in turn, encourages further reworking of sediment and eventually leads to collapse of the system. Once a barrier is unstable it is likely that internal feedback mechanisms and critical thresholds will enhance degradation and lead to rapid breakdown of the system (Orford et al., 2002). It is suggested that the complicated interaction between decreasing sediment supply in relation to accommodation created by both existing basement topography and rapid rates of relative sea-level rise, together with internal reorganisation through breaching and reworking of sediment bodies are probably responsible for breakdown of the barrier at Hastings Bank.

4.5.3 Barrier retreat

Once a barrier starts to break down it becomes more susceptible to positional instability (Orford et al., 2002). At Hastings Bank, barrier retreat is represented by LE Phase 4 where the barrier, including the seaward barrier shore is drowned, and LE Phase 5 where remnants of the back-barrier are preserved. In both cases the barrier is overstepped (Fig. 4.1). However, a distinction between the style of retreat can be made in relation to net sediment budget, i.e. the relative balance between total sediment supply (offshore, up-drift and reworked components) in relation to accommodation (basement topography vs. sea-level rise) (cf. Nichols, 1989), namely a ‘sediment deficit’ overstepping where the shoreface facies are reworked due to a relative excess of accommodation linked to basement topography and/or relative sea-level rise and, hence, shoreface reworking, and ‘sediment surplus’ overstepping whereby the shoreface facies are preserved (Fig. 4.12). Assigning an age to each of these phases of retreat is not possible. However, the chronology presented in section 4.4.4 and Figure 4.10, suggests they occurred after 8.3 ka and before 7 ka. Present understanding of the conditions that determine the nature of barrier retreat during transgression, i.e overstepping vs. rollover, is based on a few rare examples where barriers are preserved during transgression (Forbes et al., 1991; Roy et al., 1994; Storms et al., 2008; Hijma et al., 2010) and numerical models (Storms et al., 2002; Storms and Swift, 2003). According to this understanding, barrier retreat is considered to be controlled by substrate slope, sediment supply, rate of sea-level rise and back-barrier accommodation.

Initial retreat (LE Phase 4) after barrier breakdown is through 'sediment surplus' overstepping (Fig. 4.12) whereby the shoreline is abruptly displaced landward leaving the barrier complex submerged offshore. Typically, overstepping usually preserves only the back-barrier deposits (Forbes et al., 1991; Storms and Swift, 2003; Storms et al., 2008). However, at Hastings Bank shoreline displacement is significant enough to avoid reworking of the shoreface and the barrier shore remains intact. Preservation of the entire barrier, including the shoreface, is exceptionally rare and lacks definition within sedimentological nomenclature. Hastings Bank is therefore an ideal example with which to examine the conditions under which a barrier can become completely submerged during transgression.

The timing of initial retreat (LE Phase 4) corresponds to a period of rapid post-glacial sea-level rise when globally, relative sea-level rise was ca. 13 m/ka (Smith et al., 2011), exceeding a modelled rate for barrier overstepping of 3.3 m/ka (Storms et al., 2002). A significant jump and/or rapid rise in sea-level and a moderate to weak wave climate would be required to abandon the barrier below wave base without reworking. Shallowing of the substrate underlying the barrier would have enhanced the rate of transgression. Further, an increase in tidal amplitude, such as is simulated for the early Holocene when the Straits of Dover opened (Uehara et al. 2006), would encourage a rapid rate of transgression across the shelf (Storms et al., 2008). Interactions between the above conditions would have encouraged a scenario where a barrier can be overstepped.

During rapid transgression, the potential for drowning and abandonment of barrier landforms and sediments is influenced by sediment availability. Where this is high, the shoreline is able to retreat without significant sediment reworking, thus increasing the preservation potential of coastal deposits offshore. This is demonstrated through exceptional preservation of both barrier shore and back-barrier beach landforms at Hastings Bank (Fig. 4.12). Prior to drowning, the barrier is in a phase of breakdown as sediment is recycled both alongshore and cross-shore in an attempt to maintain supply to balance accommodation in the back-barrier environment, via washover and tidal breaching. Once this space is completely filled, sediment availability relative to accommodation increases and the supply is sufficient enough to prevent reworking of the shoreface (Storms and Swift 2003), encouraging the barrier to drown in place. At the time of drowning the barrier is stationary and relatively resilient to change. In this morphodynamic state, the barrier was not forced to respond to relative sea-level rise through rollover and alongshore reworking, and instead, responded with a landward displacement of the shoreline.

After initial drowning, barrier retreat is through 'sediment deficit' overstepping with erosion of the shoreface and preservation of landward stepping back-barrier deposits (Fig. 4.12). Rapid rates of relative sea-level rise continue through the early Holocene (Smith et al., 2011) and are therefore sufficient to encourage overstepping. A change in the style of barrier retreat from 'sediment surplus' to 'sediment deficit' overstepping may have been influenced by a meltwater driven sea-level jump (eg. Hijma and Cohen, 2010). However, this is speculative and a chronometric framework is required to test this.

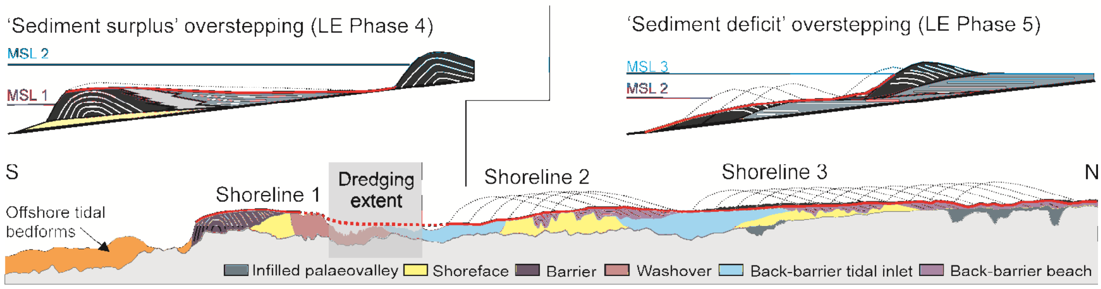


Figure 4.12: Style of barrier retreat during sea-level transgression according to the depositional record preserved at Hastings Bank. Transgression is represented by mean sea level (MSL) 1, MSL 2 and MSL 3. Thick red line is an erosional surface; continuation of this surface within the area reworked by dredging activities is represented by the red dashed line. The black dashed line indicates the morphology of former shorelines.

Substrate slope is relatively constant between the barrier and the present day coast and assuming no major change in the rate of relative sea-level rise, the style of barrier retreat would have been strongly influenced by sediment availability. Initial drowning of the barrier represents a phase of positional instability where the barrier becomes more susceptible to reworking (cf. Rollover) (Orford et al., 2002). Erosion of the barrier as it migrates landward implies disequilibrium between sediment supply and accommodation in the back-barrier (Storms and Swift, 2003). As the barrier migrates landwards, alongshore sediment transport is no longer limited by the topography of Hastings Palaeovalley and offshore to onshore sediment transport, via washover and tidal breaching, is less pronounced. Development of a large sand and gravel barrier alongshore at Dungeness from 5 ka onwards (Long et al., 2006; Roberts and Plater, 2007) required a supply of sediment from offshore (Jennings and Smyth, 1990). Hastings Bank is the most likely source, where, during phases of low resilience and overstepping, sediment is transported alongshore to feed development of the new barrier complex.

Preservation of barrier deposits, including those of the barrier shoreface and shoreline, appears to be a function of the style of retreat (Fig. 4.12), which, using Hastings Bank as an example, is principally conditioned by the rate of transgression, sediment supply and transport vector and accommodation created by rising sea levels and inherited topography. In addition, preservation post-submergence is influenced by sedimentary facies and architecture. Finer grained shoreface sands and back-barrier muds are only preserved when gravel barrier deposits have built upon them or migrated over them. Gravel on the seabed is immobile under present-day tidal and wave regimes in the region (Cazenave, 2007), thus the gravel forms a protective amour that shields underlying finer grained deposits from reworking through tides and waves (e.g. Wright, 1971) and enhances seabed resilience and preservation of the barrier complex.

4.6 CONCLUSIONS

Drowned landscapes and their associated deposits are important sedimentological and geomorphological archives that can improve our understanding of environmental response to abrupt climatic and sea-level change across the terrestrial to shallow marine continuum. With increased exploration of the seabed and improved knowledge of rapid rates of sea-level rise characteristic of early interglacial periods, it is expected that further drowned coastal landscapes will be identified and characterised. Through integration of reflection seismic profiles and vibrocore datasets, a robust stratigraphic framework enabled detailed reconstructions of landscape evolution. Using Hastings Bank as a case study, a palaeogeographic reconstruction from sub-aerial lowstand through transgression to submerged highstand settings has been completed.

A particular characteristic landform recognised is an exceptionally well-preserved gravel barrier with both extant seaward and landward portions preserved, due to a marked rise in relative sea-level and high sediment availability. It is demonstrated that the style of barrier overstepping is principally driven by the relationship between sediment availability, rate of sea-level rise, back-barrier accommodation and inherited topography. Without a chronological constraint, it is not possible to quantify the relationships between the processes forcing discontinuous barrier retreat. However, the Hastings Bank site presents an ideal field laboratory to test models of morphodynamic response and resilience of coarse clastic coasts to different rates of relative sea-level rise that can be used to constrain future projections of coastal response to climate change.

Acknowledgements

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Chapter 5

Optical dating of drowned landscapes: a case study from the English Channel

Abstract

Drowned landscapes are important archives documenting palaeoenvironmental response to abrupt climate and sea-level changes characteristic of the Quaternary. Analysis of high resolution geophysical and core data has revealed preservation of fluvial, coastal, shallow marine and periglacial deposits on the continental shelf in the eastern English Channel, thus providing an ideal field site to test the application of optical dating to a variety of depositional environments presently submerged beneath the sea. A stratigraphic model detailing the sequence and nature of sedimentary processes operating on the shelf in relation to post-glacial relative sea-level change is presented as a framework to test the reliability of optical ages. The single-aliquot regenerative-dose protocol was applied to 1 mm aliquots of fine quartz sand and individual aliquots were rejected following the criteria proposed by Wintle and Murray (2006). All samples demonstrate a range of intrinsic sensitivities with a sufficient number of grains giving enough light to enable reliable estimation of D_e. Different age models, CAM and MAM-3, were used to establish palaeodose and the robustness of these age models was tested using a bootstrapping technique. Coastal sediments show evidence of incomplete bleaching limiting confidence in age estimates. Quartz deposited in fluvial, periglacial and shallow marine environments is suitably bleached and OSL sensitive to enable reliable estimates of D_e. Changes in environmental dose must be considered when interpreting ages from sediments that have experienced repeated relative sea-level cycles. Ages in the range of 107.8 ka to 5.3 ka were calculated that are remarkably consistent with the stratigraphic model, thus demonstrating the successful applicability of optical dating to drowned landscapes.

5.1 INTRODUCTION

Continental shelves submerged beneath shallow seas around the world are archives for a wealth of geomorphological, sedimentological and archaeological landscapes (Browne, 1994; Fitch et al., 2005; Baldwin et al., 2006; Bailey and Flemming, 2008; Shaw et al., 2009;

Alappat et al., 2010). These drowned landscapes have significant potential for extending our understanding of palaeoenvironmental responses to rapid sea-level fluctuations and abrupt climate changes characteristic of the late Quaternary. The continental shelf surrounding the UK flooded rapidly during the early Holocene (Smith et al., 2011). Subsequent low sedimentation rates have ensured preservation of a range of landforms and stratigraphies that document landscape evolution over time periods that are poorly represented onshore (Fitch et al., 2005; Ward et al., 2006; Gaffney et al., 2007; Gupta et al., 2007; Bradwell et al., 2008; Hijma et al., 2010).

Despite being characterised by sedimentary bypass to the deep ocean over glacial to interglacial sea-level cycles, the submerged continental shelf in the eastern English Channel provides an opportunity to examine the interaction of terrestrial (slope and fluvial), coastal and shallow marine landscapes and stratigraphies over such cycles. However, to accurately assess their linkages and process-response to relative sea-level change, a chronological framework is required. On the English Channel continental shelf, clastic sediments are more abundant than organic material that has an unequivocal stratigraphic context, limiting the applicability of radiocarbon dating as a chronometric tool. Optically Stimulated Luminescence (OSL) dating (optical dating) offers the opportunity to determine the time of sediment deposition by dating the last exposure to daylight of silt or sand sized quartz or feldspar grains. Optical dating has been used successfully across a range of depositional settings encompassing, aeolian, fluvial, coastal and marine, periglacial and glaciofluvial systems. Deposition of sediments on the eastern English Channel continental shelf over glacial to interglacial cycles is attributed to sedimentary processes associated with one or more of the above palaeoenvironments. The eastern English Channel is therefore an ideal field site to test the suitability of optical dating in drowned landscapes and address issues relating to: (i) quartz provenance on continental shelves; (ii) changes in water content during periods of submergence and sub-aerial exposure, and; (iii) attenuation of cosmic dose in drowned landscapes. Uncertainties associated with ages are discussed in light of: (i) bleaching of quartz OSL in fluvial, coastal, marine and cold climate terrestrial environments; (ii) quartz OSL signal properties, and; (iii) dose rate estimation. The resultant ages provide the first stratigraphically-constrained chronometric control on deposition in the eastern English Channel allowing an insight into the sequence and timing of landscape evolution in this region.

5.2 SETTING AND STRATIGRAPHY

The English Channel is a narrow seaway that separates the British Isles from the European continent (Fig. 5.1a). It is at its narrowest at the Straits of Dover and the area referred to in this paper as the eastern English Channel (Fig. 5.1b) lies ~100 km west of the Straits of Dover in present-day water depths of -10 m to -60 m Ordnance Datum (OD). The seabed is part of a shallowly dipping (0.3° – 0.5°) continental shelf that extends ca. 600 km south-westwards to the continental shelf-edge break in present day water depths of –140 m OD. Bedrock geology is controlled by Cretaceous strata (clay, sandstone and chalk) of the Weald Artois anticline and Tertiary (clay and sandstone) strata of the Hampshire Dieppe basin (Hamblin et al., 1992).

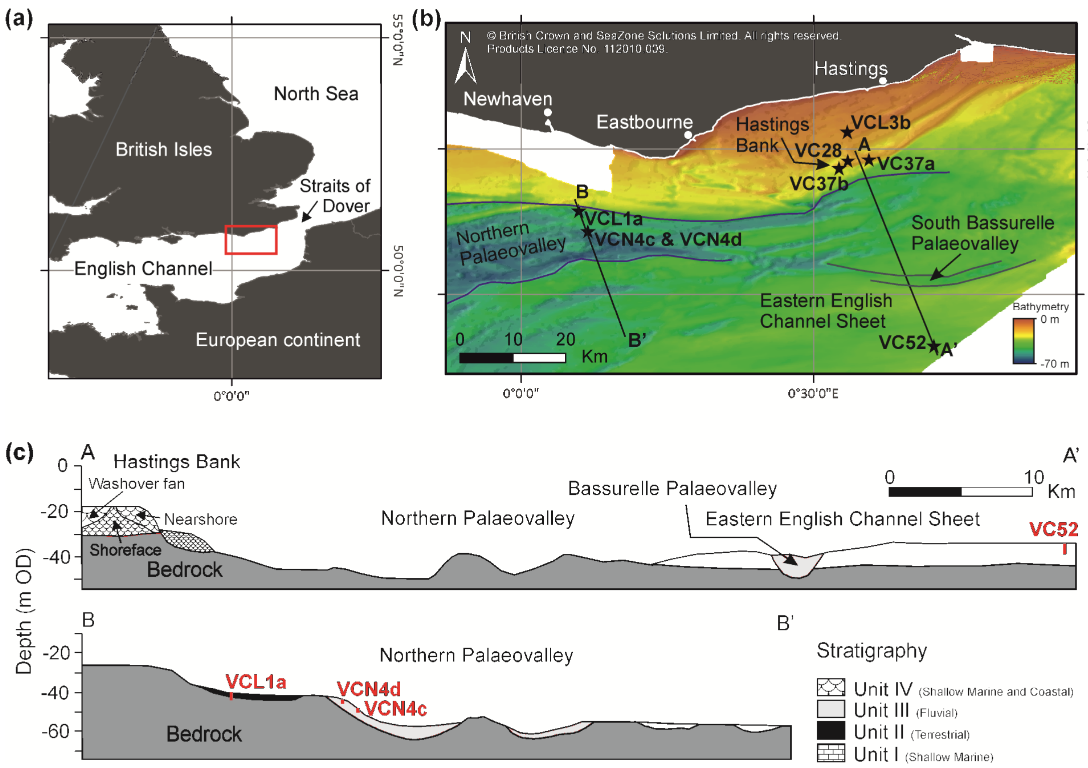

Figure 5.1: (a) Location of English Channel in northwest Europe. (b) Location of eastern English Channel showing seabed bathymetry and vibrocore sampling positions. Key morphological features referred to in the text are illustrated. Location of cross-sections referred to in Fig. 5.1c are shown as black lines. (c) Stratigraphic model illustrating extent and thickness of sediments and stratigraphic relationship between deposits. Vibrocores are shown as red lines where they intercept cross-sections and plotted to scale on the vertical axis.

Stratigraphic Unit	Diagnostic characteristics	Depositional environment	Core	Depth (m OD)	Sample Code	Proposed age
IV	Seaward prograding inclined seismic reflectors. Massive to horizontally bedded sands with a minor fine gravel component and occasional fine mud laminae	Shallow marine (shoreface)	VCL3b	-13.7	LV409	OIS 1
		Shallow marine (shoreface)	VC28	-19.11	LV401	OIS 1
	Aggrading and landward prograding, chaotic and complicated seismic reflectors. Poorly sorted matrix supported gravels	Coastal (washover fan)	VC37a	-16.81	LV407	OIS 1
	Landward and seaward prograding inclined seismic reflectors separated by convex upward aggrading seismic reflectors. Clast supported gravels interbedded with massive sands including a minor gravel component and Fe/organic mottles	Coastal (nearshore beach)	VC37b	-24.02	LV408	OIS 1
III	Lateral progradation of inclined seismic reflectors. Matrix supported gravels interbedded with silty fine sands	Fluvial (bar)	VCN4c	-53.2	LV403	OIS 2
		Fluvial (bar)	VCN4d	-52.7	LV402	OIS 2
		Fluvial (bar)	VCN4d	-53.4	LV411	OIS 2
II	Progradation of inclined seismic reflectors downslope. Very poorly sorted clayey silty sandy gravels	Terrestrial (periglacial slope)	VCL1a	-53.1	LV451	OIS 2
I	Low amplitude wavy parallel seismic reflectors. Very well sorted massive sands	Shallow marine (shoreface)	VC52	-44.8	LV452	>OIS 2

Table 5.1. OSL samples and sedimentary characteristics. Stratigraphic unit diagnostic characteristics based on seismic stratigraphy and lithofacies analyses.

Interpretation of over 200 vibrocores tied to a high resolution (<1 m vertically), closely spaced (0.08-3 km) sub-bottom 2D seismic grid provided a framework to establish depositional environments, and the nature of processes responsible for landscape development in the eastern English Channel. A schematic model outlining the extent, thickness and stratigraphy of deposits preserved in the eastern English Channel is presented in Fig. 5.1c and key diagnostic seismic and lithological signatures used to inform interpretations are summarised in Table 5.1 (see also Chapter 4 and Chapter 6). According to the proposed model, samples taken for optical dating originated from: (i) shallow marine; (ii) coastal; (iii) fluvial, and; (iv) slope periglacial depositional environments. Interpretation of stratigraphic units in relation to sea-level changes during the Quaternary, allows deposition to be constrained within Oxygen Isotope Stages (OIS).

5.3 METHODS

5.3.1 Experimental details

During a survey in March 2010 individual stratigraphic units were targeted for the collection of samples for optical dating (see Fig. 5.1b for locations). Samples were collected using a high powered C-CoreHP vibrocorer and recovered in 85 mm-diameter opaque plastic liners. The cores were immediately sealed and transported to the laboratory where they were split and sampled under laboratory safe light conditions (Mauz et al., 2002). Samples were extracted from the centre of the core and the surrounding 1 cm of sediment was collected for dose-rate determination and water content measurements.

Samples of 90-180 µm grain size were treated with 35% (weight/volume) HCl and H_2O_2 to remove carbonates and organic matter, respectively. Quartz was separated from feldspar and heavy minerals using lithium polytungstate solution at densities of 2.76 g cm^{-3} and 2.62 g cm^{-3}. Quartz grains were etched with 48% HF for 40 min to remove the outer part of the grain affected by alpha radiation. Subsequent to etching, quartz grains <63 µm were removed. The remaining grains were mounted on stainless steel discs using silicon oil covering the central 1 mm. Due to low intrinsic OSL sensitivity, aliquots of 3 mm size were used for sample LV411. The number of grains present on an aliquot was determined by counting grains on a sub-set of aliquots (n=10) from each sample. The average of these grain counts is given in Table 5.2. Whilst it is not possible to ascertain the number of luminescent grains per aliquot without single-grain analysis, following Duller (2008a), approximately 5% of grains are expected to dominate the luminescence signal.

All D_e measurements were carried out using an automated Risø DA-15 reader equipped with an EMI 9235QB photomultiplier. Optical stimulation was carried out with blue light emitting diodes (470Δ30 nm) at a temperature of 125 °C for 40 s delivering ~30 mW cm^{-2} at 90% power. The sensitivity-corrected natural and regenerated OSL (L_x, T_x) values were derived from the integral over the first 0.32 s subtracted by the integral over the last 3.2 s of the OSL stimulation.

5.3.2 Equivalent dose determination

Dose recovery preheat tests were carried out to assess the effect of thermal treatment upon equivalent dose (D_e). D_e values were estimated using the SAR protocol (Murray and Wintle, 2000). Exponential, linear or exponential + linear dose response curves were generated depending on signal growth characteristics of each sample. For all measurements individual aliquots were rejected if the following criteria were not met: (i) high and low recycling ratios within 1 ± 10% (Wintle and Murray, 2006); (ii) recuperation signal smaller than 5% of the sensitivity corrected natural signal (Wintle and Murray, 2006); (iii) OSL-IR depletion ratio within 1 ± 10% (Duller, 2003); (iv) L_n/T_n smaller than the sensitivity corrected maximum regenerative dose (L_{max}/T_x); (v) OSL decay at background after ~4s stimulation time, and: (vi) Initial OSL response to test dose signal >300 counts/0.32 s.

5.3.3 Dose-rate determination

The concentration of K, Th and U in the sediment was determined using high resolution, low-level gamma spectrometry. Samples were packed and sealed in airtight plastic containers and stored for ~4 weeks prior to analysis in order to equilibrate ^{226}Ra and ^{222}Rn (for further details see Mauz et al., 2002). Within the limits of this method no secular disequilibrium in the Uranium chain was observed. Radioisotope concentration (ppm) determined from the measured activity was converted to annual dose rate (Gy ka^{-1}) using conversion factors provided by Adamiec and Aitken (1998) and corrected using factors for beta attenuation in grains (Brennan, 2003).

Exposure of samples to cosmic rays is variable over time in drowned landscapes as subsequent to burial they are sub-aerial exposed and then later submerged in a fully marine environment. Using a relative sea-level curve (Lambeck et al., 2002) and an initial age estimate for each sample, the proportion of time since burial that the sample rested in a terrestrial or marine environment was assessed. Attenuation of cosmic dose through the sediment column in terrestrial environments was derived from the mean burial depth of the samples (Prescott and Hutton, 1994). Attenuation of cosmic dose through the overlying water column was calculated following Aitken (1985). Attenuation of cosmic dose in drowned landscapes was modelled using the following assumptions: (i) sea level was above – 60 m OD from 125 ka to 70 ka; (ii) sea level was below -50 m OD from 70 ka to 10 ka; (iii) changes in sea level were linear, and; (iv) sea level reached present day OD at 7 ka. A 5% uncertainty was assigned to the cosmic dose estimates following Prescott and Hutton (1994).

The effective dose rate due to water content (Aitken, 1985) was calculated on the basis of in-situ water content measured subsequent to sampling. As a consequence of submergence beneath a water column for long periods of time (>7 ka), in-situ water content is expected to be close to saturation. The effect of post-depositional variations in water content on dose rate since burial is expected to be low given that samples were close to saturation for a large proportion of their burial history. Despite this, uncertainties were estimated from potential maximum and minimum values for each depositional setting and are discussed in section 5.5.3.

5.3.4 Age models

To characterise D_e distributions over-dispersion (σ) calculated using the algorithm of the central age model (CAM) (Galbraith et al., 1999), weighted skewness (c) and standardised kurtosis (k) (Bailey and Arnold, 2006; Arnold and Roberts, 2009;) were used (Table 5.2). The appropriateness of different age models was assessed according to: (i) over-dispersion (MAM-3>20%>CAM), and; (ii) critical skewness value of $\pm 1\sigma_c$ (Arnold et al., 2007) applying the decision protocol of Bailey and Arnold (2006).

To test the robustness of the age models a bootstrapping technique was applied. D_e estimates for each sample were resampled at random to create 20 subsamples that contained 60-70% of the accepted D_e estimates. The appropriate age model was then used on each of the subsamples including σ_b=10% and the mean and standard deviation of the modelled D_es calculated. Where MAM-3 was used, model D_es derived from <10% of the total D_e population (δ) were rejected to ensure less significant components of the overall population were not included. For age calculation the mean and 1σ error of the modelled D_e values from the bootstrapping approach were used. Values for model D_es (calculated using all accepted aliquots) and D_es based on the bootstrapping (mean and standard error) are listed in Table 5.3.

5.4 RESULTS

5.4.1 Appropriateness of SAR protocol

The results from preheat tests of representative samples from each depositional setting are shown in Fig. 5.2. Samples deposited in terrestrial environments (LV411 and LV451) showed strong coherence between given dose and recovered dose at all preheat (PH_1) temperatures up to 250°C. In comparison, ~40% of aliquots were rejected across the full range of PH_1 temperatures in samples from shallow marine/coastal settings (LV407 and LV409). Preheat temperatures of 240-250°C were chosen depending on the results of preheat dose-recovery tests for individual samples. The ability to recover an accurate dose above PH_1 temperatures of 250°C decreases across the full range of depositional settings.

5.4.2 Quartz OSL signal properties

Rejection statistics are comparable across the full range of depositional settings with rejection of the majority of all aliquots measured due to low test dose OSL signal or poor recycling ratios as a function of these dim signals. In light of this, the ratio of accepted/measured aliquots (Table 5.2) and OSL response to test dose signal (Fig. 5.3a) can be viewed as a proxy for intrinsic sensitivity. Sensitivity changes do not appear to be a function of preheat temperature as demonstrated on Fig. 5.2c. Typical OSL decay and dose response curves for accepted aliquots from each depositional setting are shown in Fig. 5.4. Slightly higher rejections rates are observed for samples LV407 and LV408 extracted from coastal depositional settings (85% of aliquots rejected) in comparison to samples taken from all other environments (on average 75% of aliquots rejected). Sensitivity changes do not appear to be a function of palaeodose as a range of intrinsic sensitivities are observed across the full range of equivalent doses (Fig. 5.3b). Where aliquot size, grain size and given test dose are identical (LV407 and LV408, coastal, and; LV401 and LV409, shallow marine) an assessment of changes in OSL sensitivity between depositional settings can be made.

Approximately 50% of aliquots from sample LV452 were rejected due to an OSL signal close to saturation. The average $\overline{\boldsymbol{D_0}}$ value (Table 5.2) for all accepted aliquots is less than $2\overline{\boldsymbol{D_0}}$ ensuring aliquots used in D_e are suitable for age determination.

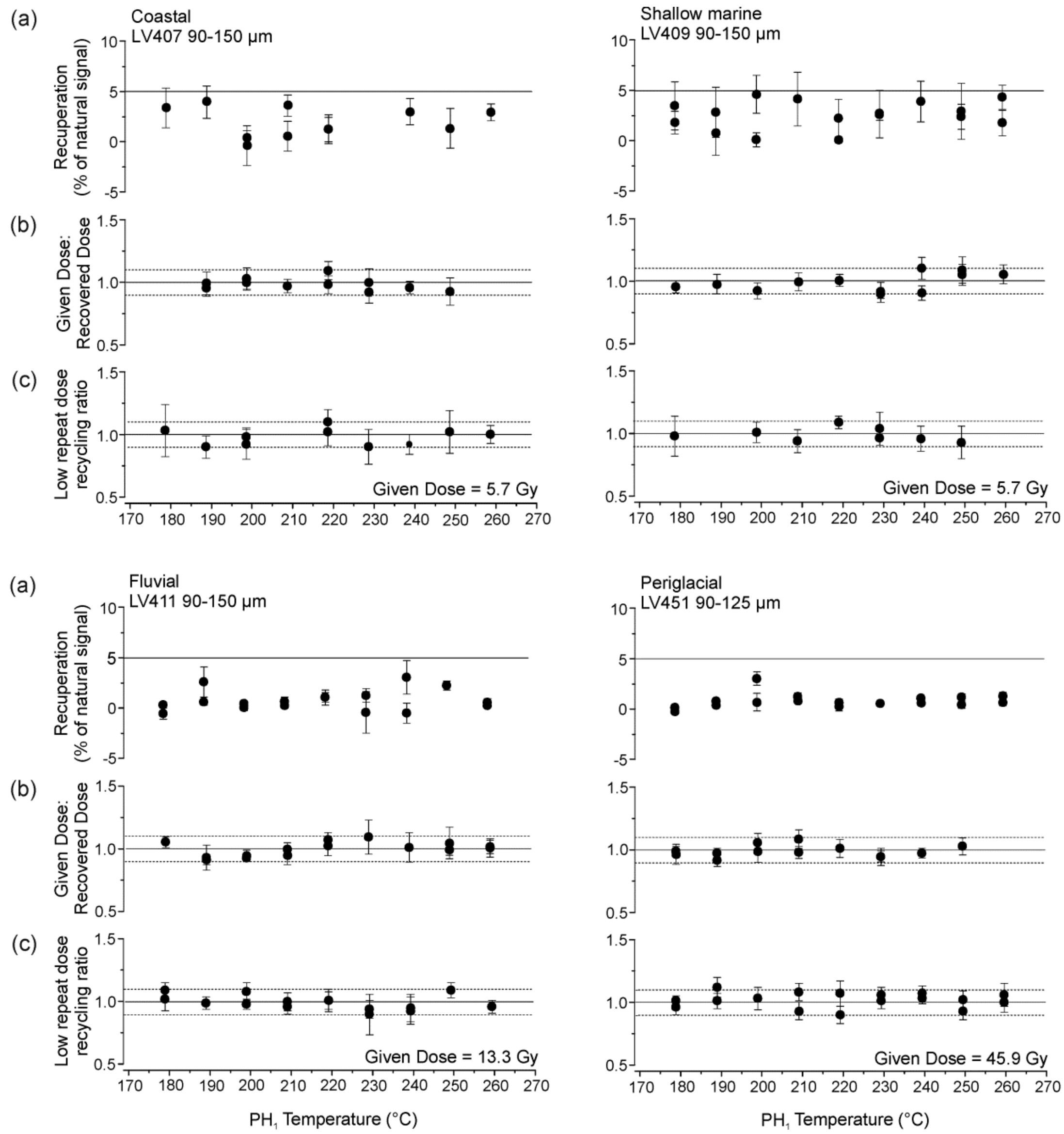

Figure 5.2: (a) Recuperation as a percentage of the natural signal plotted against PH_1 temperature for samples representing each depositional context. Filled circles show thermal transfer (% of the natural signal) of individual accepted aliquots and 1σ errors. 5% is used as rejection criteria (Wintle and Murray 2006) and is highlighted as solid black line. (b) Ratio of given dose to recovered dose (accepted aliquots only) plotted against PH_1 temperature for samples representing each depositional context. Filled circles represent individual aliquots and 1σ errors. The solid black line represents unity; the dashed black lines indicate unity ± 10%. (c) Low repeat dose recycling ratio as a function of PH_1 temperature for representative samples from each depositional setting. Filled circles represent accepted aliquots and 1σ error bars. The solid black line indicates unity; the dashed black lines delimit unity ± 10%.

.

Sample code	Aliquot (accepted/ measured)	Grain size (μm)	Aliquot size (mm)	Grains per aliquot; predicted	Grains per aliquot; counted	Luminescent grains per aliquot	Descriptive Statistics					$\overline{D_o} \pm \sigma$ (Gy)	Statistical age model
							σ (%)	c	$1\sigma_c$	k	$1\sigma_k$		
LV401	39/192	63-150	1	75-120	25	1	12	0.21	0.39	0.57	0.78		CAM
LV402	56/168	63-180	1	60-120	40	2	17	-0.20	0.33	-0.30	0.65		CAM
LV403	52/216	63-150	1	75-120	25	1	18	0.46	0.34	0.85	0.68		CAM
LV407	40/264	63-150	1	75-120	25	1	23	0.44	0.39	0.65	0.77		MAM-3
LV408	46/288	63-150	1	75-120	25	1	21	0.48	0.36	1.37	0.72		MAM-3
LV409	48/192	63-150	1	75-120	25	1	11	-0.08	0.35	0.45	0.71		CAM
LV411	43/168	63-150	3	600-1300	90	5	25	-1.01	0.41	0.46	0.83		CAM
LV451	57/216	63-125	1	90-120	60	3	13	-0.18	0.32	-0.48	0.65		CAM
LV452	37/144	63-125	1	90-120	60	3	24	-0.40	0.40	-0.42	0.81	75.6 ± 31.7	CAM

Table 5.2: Detailed OSL statistics. Grain size represents the grain fraction used for measurement after etching with HF. Predicted number of grains per aliquot after Duller (2008). Average number of grains per aliquot established by counting grains present on a sub-set of aliquots from each sample. The number of luminescent grains per aliquot is calculated on the assumption that 5% of grains contribute to the luminescence signal (Duller, 2008). Descriptive statistics following Bailey and Arnold (2006) and Arnold and Roberts (2009); σ = over-dispersion; c = weighted skewness of ln D_e; $1\sigma_c$ = standard error of skewness (critical skewness score; ± $1x\sigma_c$); k = standardised kurtosis; $1\sigma_k$ = standard error of kurtosis (critical kurtosis score: ± $1x\sigma_k$); $\overline{D_o}$ is given as average value from all accepted aliquots ± 1σ; MAM-3 = minimum age model with 3 parametres; CAM = central age model.

An assessment of the number of grains present on small aliquots of varying grain sizes revealed that the actual number of grains per aliquots is typically less than that proposed by Duller (2008a) (Table 5.2). A pattern observed across all samples is depicted on Fig. 5.3a where aliquots are dominated by dim grains yielding <500 counts/0.32 s. The distribution of sensitivities shown in Fig. 5.3b indicates that multi-grain aliquots are dominated by a signal derived from a few, if not one grain only and that the sensitivity of the quartz grains is not dependent upon palaeodose. In addition, the fact that a large number (up to 85%) of aliquots are rejected due to low OSL signal in response to a reasonable test dose indicates that the majority of grains present on a small aliquot do not emit light. Thus, in the case of the eastern English Channel, small aliquots are considered an adequate proxy for single-grains.

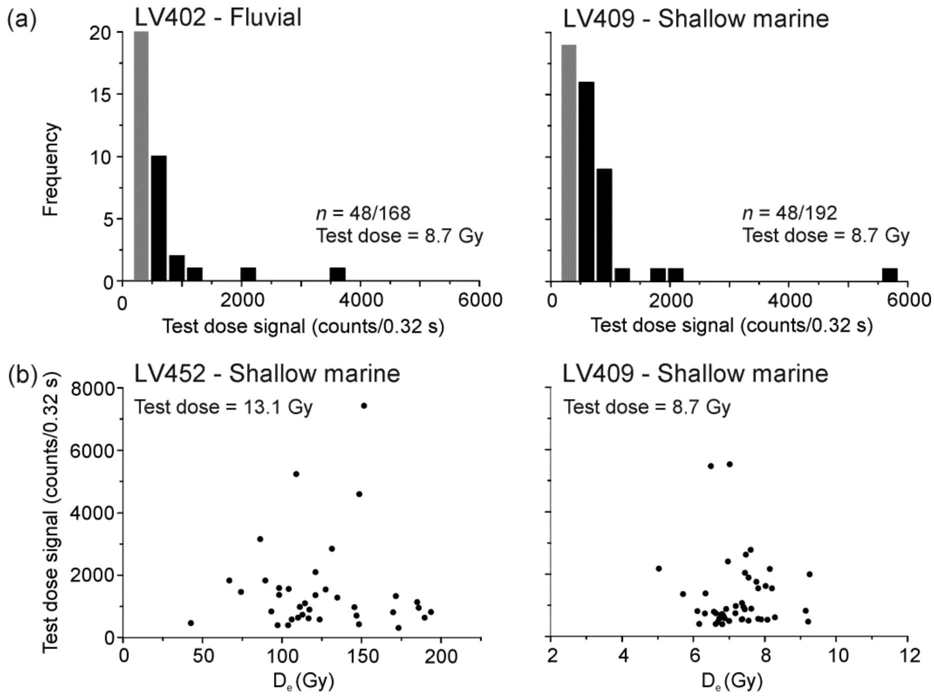

Figure 5.3: (a) Frequency histogram of test dose signal. n = a representative subsample of aliquots/total number of aliquots measured. Grey bar shows aliquots rejected due to a test dose signal of <300 counts/0.32 s. (b) Test dose signal plotted against D_e.

5.4.3 D_e distribution and age calculation

All samples exhibit log normal D_e distributions, with the exception of LV451, which is normally distributed across a broad range of D_es (Fig. 5.5). The ln D_e frequency histogram for sample LV407 shows a positively skewed log normal distribution of values. All other samples demonstrate normal ln D_e distributions. The distribution of ln data, over-dispersion values of <20% and critical skewness values of <2σ_c indicate that insufficient bleaching is not an issue for most samples with the exception of LV407 and LV408. The D_e distribution of LV407 indicates heterogeneous bleaching. Over-dispersion values are <20% for five of the nine samples measured and <25% for all remaining samples. There is no apparent trend between over-dispersion values and depositional environment. See Table 5.2 for descriptive statistics and Fig. 5.5 for D_e and ln D_e distributions.

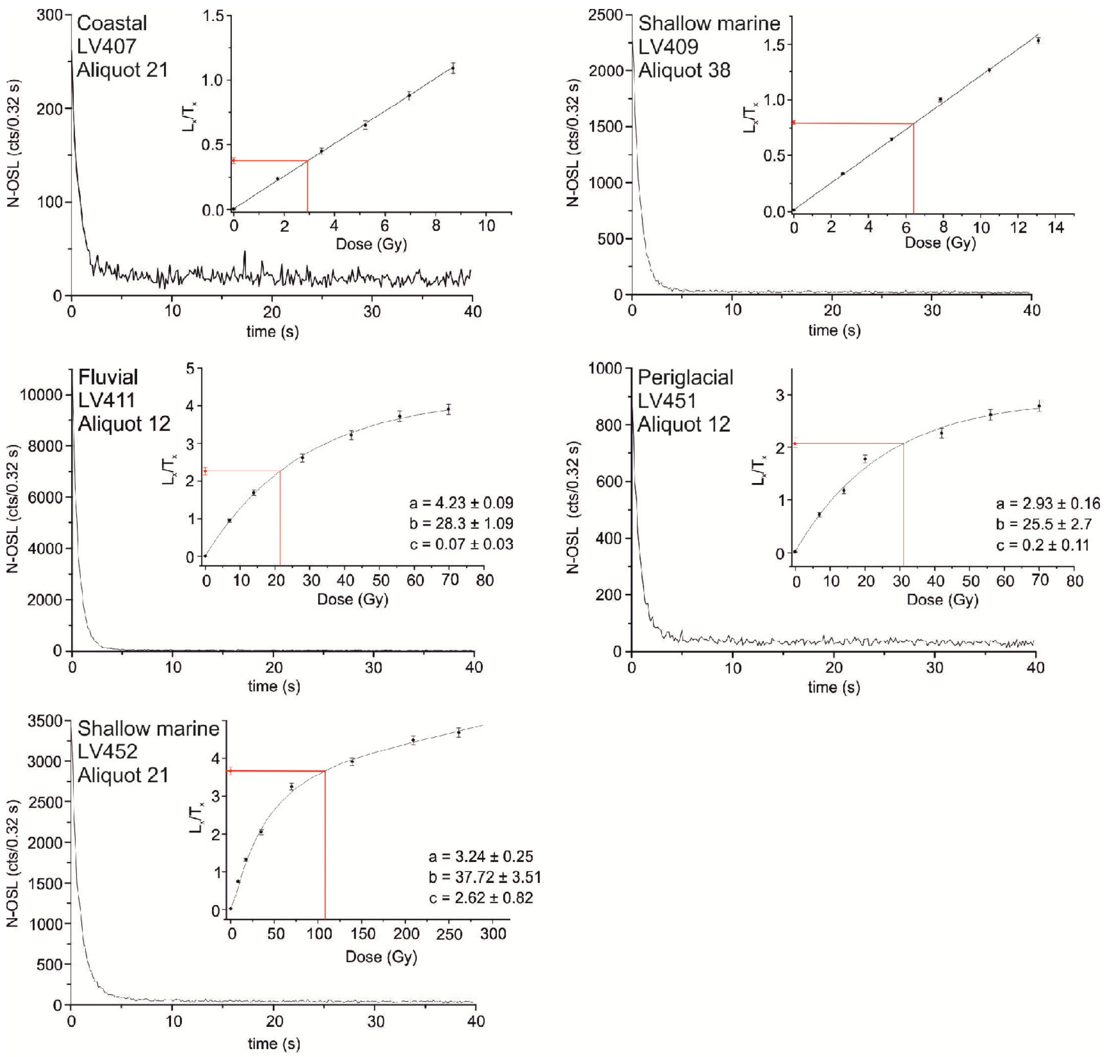

Figure 5.4: OSL decay curves and dose response curves for samples representing each depositional setting

For sample LV401, LV402, LV403, LV409 and LV451, CAM was considered the most suitable model due to σ<20% and *c*<0.2. For sample LV452 the ratio, mean D_e/D_0 = 1.80 was used as the basis for choosing CAM as the appropriate age model. Given the proportion of aliquots rejected due to OSL saturation, it is inferred that the D_e distribution of sample LV452 is the result of different saturation levels of the quartz grains and not a function of bleaching confirming Bailey and Arnold (2006) who show a sub-linear relationship between σ and geological dose. Model and boot-strapped D_es calculated from the CAM are within 1σ of the mean of all accepted aliquots (Table 5.3).

Over-dispersion values > 20% and critical skewness values $\pm 1\sigma_c$ led to the application of MAM-3 to LV407 and LV408. The resulting D_e for LV407 (3.0 ± 0.9 Gy) is within 1σ of the mean D_e (4.2 ± 1.1 Gy). Through the application of bootstrapping, statistical outliers were identified and lower D_es removed.

Ages in the range of 5.3 ka to 107.8 ka were calculated for a range of landscapes submerged beneath the English Channel. Parameters used to calculate ages are shown in Table 5.3. The resultant ages are remarkably consistent with the proposed stratigraphic model placing deposition of: (i) shoreface sediments at 107.8±5.2 ka, (ii) fluvial and terrestrial sediments between 17.9±0.7 ka and 15.8±0.9 ka, and (iii) shoreface and coastal sediments between 8.0±0.6 ka and 5.3±0.5 ka. Whilst there is no independent chronological control for these samples, ages are considered accurate given sea-level history of the English Channel. Sample LV411, taken at a depth of -53.4 m OD is younger than LV402 taken at -52.7 m OD. Despite being stratigraphically inconsistent within the core, ages for these samples are identical within 1σ errors.

5.5 DISCUSSION

The reliability of OSL ages is largely dependent on changes in environmental conditions during erosion, transport, deposition and burial of quartz. Where independent dating control is absent, confidence in age estimates can be qualitatively assessed by considering: (i) bleaching regime, (ii) quartz OSL signal properties, and (iii) changes in dose rate over time. Samples from the eastern English Channel are discussed in light of each the above topics and confidence in age estimates is qualitatively assessed and outlined in Table 5.4.

5.5.1 Bleaching regime

Through analysis of D_e and ln D_e distributions, samples taken from fluvial, shallow marine and periglacial deposits are considered sufficiently bleached to enable reliable estimates of D_e values. Samples taken from coastal environments show evidence of partial bleaching (see section 5.4.3.1) and, therefore, resultant ages should be interpreted with caution.

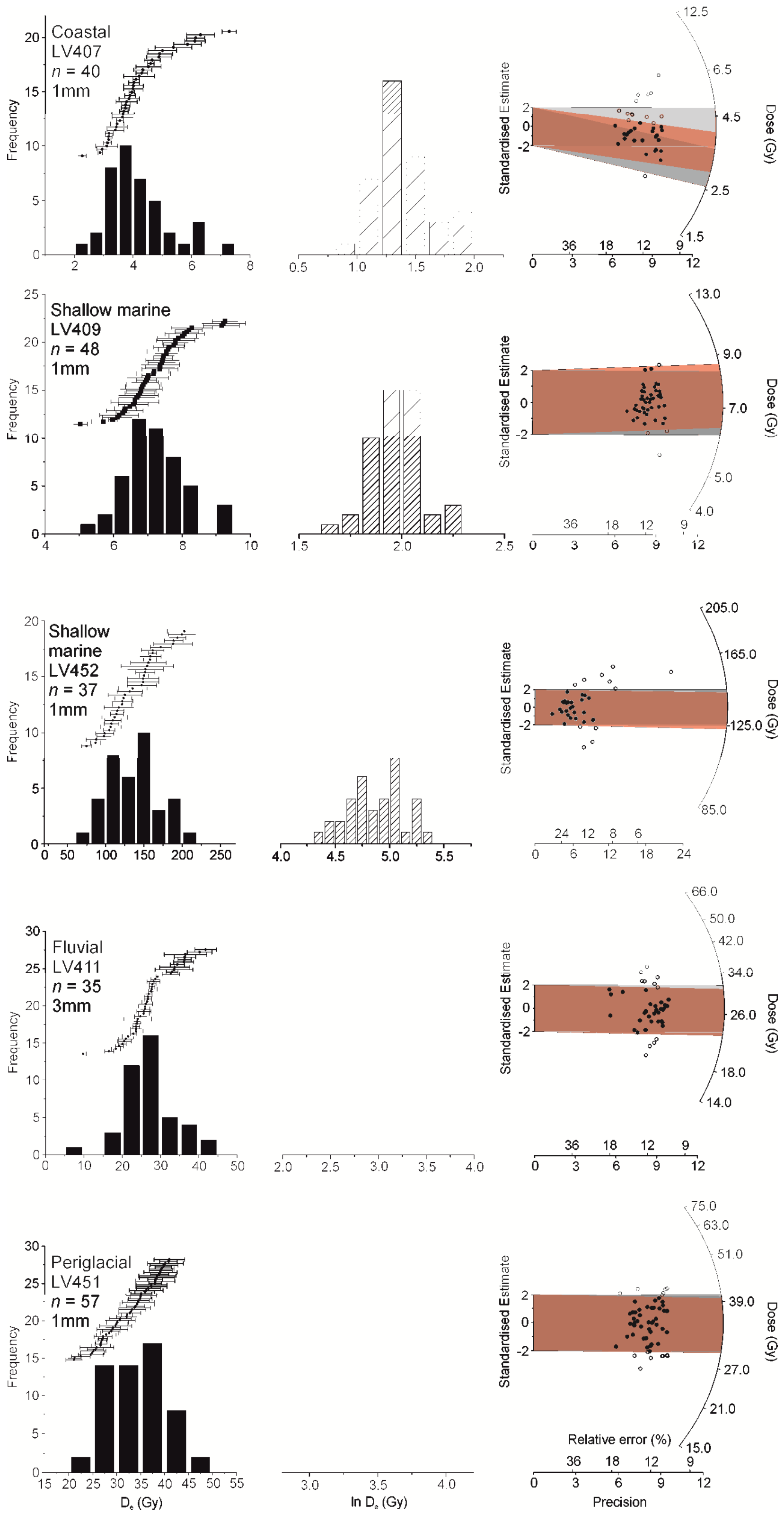

Figure 5.5: Dose distributions for all accepted aliquots: (a) black histogram showing D_e values and ranked D_e estimates, hatched histogram showing ln D_e values; (b) radial plot, light grey bar = mean D_e, dark grey bar = modelled D_e, red bar = model boot-strapped D_e

Sample Code	U ($\mu g\ g^{-1}$)	Th ($\mu g\ g^{-1}$)	K (%)	$\dot{D}_{cosm}$ (Gy ka^{-1})	Water Content (%)	$\dot{D}$ (Gy ka^{-1})	D_e mean (Gy)	D_e model (Gy)	Model parameter values	D_e model boot-strapped (Gy)	OSL age (ka)
LV401	0.631 ± 0.024	1.541 ± 0.069	0.608 ± 0.017	0.031	15±3	0.81 ± 0.02	6.3±1.0	6.2±0.8		6.3±0.1	7.8±0.2
LV402	1.608 ± 0.045	4.933 ± 0.117	1.263 ± 0.030	0.084	14±5	1.84 ±0.08	31.5±5.8	31.2±5.1		31.4±0.5	17.1±0.8
LV403	1.756 ± 0.046	5.538 ± 0.122	1.385 ± 0.033	0.084	15±5	2.01 ± 0.09	32.5±7.7	31.4±3.1		31.7±1.1	15.8±0.9
LV407	0.476 ± 0.020	0.842 ± 0.062	0.417 ± 0.013	0.046	11±4	0.61 ± 0.01	4.2±1.1	3.0±0.1	P = 0.35 δ = 0.01	3.2±0.3	5.3±0.5
LV408	0.538 ± 0.023	1.035 ± 0.063	0.328 ± 0.012	0.022	15±3	0.51 ± 0.01	5.2±1.3	4.0±0.1	P = 0.32 δ = 0.01	4.1±0.3	8.0±0.6
LV409	0.678 ± 0.022	1.531 ± 0.072	0.597 ± 0.016	0.050	13±3	0.84 ± 0.02	6.9±1.6	7.2±0.8		7.1±0.1	8.4±0.2
LV411	1.047 ± 0.030	3.102 ± 0.090	1.138 ± 0.027	0.084	13±5	1.52 ±0.05	26.8±6.6	26.0±6.6		25.6±0.5	16.8±0.7
LV451	2.287 ± 0.061	6.433 ± 0.162	1.049 ± 0.028	0.084	13±5	1.92 ± 0.07	34.8±6.3	34.3±3.5		34.2±0.5	17.9±0.7
LV452	0.844 ± 0.026	2.488 ± 0.083	0.901 ± 0.022	0.109	15±5	1.24 ± 0.03	137±33.4	133.3±32.4		133.8±5.4	107.8±5.2

Table 5.3: Dose rate data, equivalent doses and optical ages. For each sample U, Th and K concentrations are listed together with cosmic dose rate $\mathring{D}_{cosm}$, water content and total effective dose rate - $\mathring{D}$. An internal dose rate of 0.035 ± 0.01 Gy ka^{-1} was assumed for each samples. Also listed are mean D_e and mode D_e based on all accepted aliquots; and model parameter values in cases where MAM-3 was used. D_e model bootstrapped shows mean and 1σ error of resampled model D_e estimates. All age estimates are consistent with the stratigraphic model.

Deposition in coastal and shallow marine environments involves a range of sedimentary processes that form a collection of aeolian, beach, tsunami, storm, estuarine, lagoon and marine deposits (see Jacobs 2008 for review). The degree of bleaching can be expected to vary considerably across this range of depositional settings (Murray et al., 1995; Richardson, 2001; Ballarini et al., 2003; Roberts and Plater, 2007; Mauz et al., 2010). In the eastern English Channel, shoreface sediments are well bleached and are considered analogous to upper shoreface sediments at Dungeness where efficient bleaching of quartz was demonstrated using modern analogue bleaching experiments (Roberts and Plater, 2007).

In contrast, coastal sediments from a nearshore beach (LV408) and washover fan (LV407), most likely storm influenced, are only partially bleached. The heterogeneous composition of sediments recovered from the washover fan in the eastern English Channel, along with a chaotic complicated seismic signature, suggest deposition occurred during a high energy event, and therefore the potential for complete bleaching of the quartz is expected to be reduced. Poor bleaching of quartz deposited in the nearshore beach environment in the eastern English Channel, were bleaching potential is expected to be high due to swash-backwash processes, can be explained if: (i) the nearshore was influenced by high energy storm waves, or; (ii) the nearshore was a dynamic environment where reworking and redistribution of sediment prevented complete bleaching.

Fluvial sediments in the eastern English Channel show D_e distributions characteristic of well bleached quartz. Deposition of fluvial sediments on the continental shelf during the Quaternary requires a sea-level lowstand of a magnitude that is associated with glacial periods. Fluvial behaviour during these cold-climate (periglacial) stages can adopt braided, wandering, meandering and anastomosing styles that incise through lateral planation, creating broad shallow channels that transport and deposit coarse grained clastic sediments (Lewin and Gibbard, 2010). Samples extracted from fluvial deposits in the eastern English Channel are attributed to a laterally-migrating channel system with asymmetric preservation of lateral channel bars. It is suggested that this fluvial style creates optimum conditions for sufficient bleaching of quartz through exposure of in-channel bar surfaces during low stage flow and deposition in relatively clear, shallow water depths.

A broad distribution of D_es characterises the periglacial deposit, however the distribution of ln D_e values and an σ value of 13% (LV451) suggests quartz extracted from periglacial slope deposits in the eastern English Channel are well bleached. Exposure of periglacial deposits to sunlight and sufficient bleaching is variable in cold-climate environments but generally poor (Bateman, 2008). The distribution, therefore, is more likely to be derived from windblown grains that were later incorporated into the periglacial slope deposit. Subsequent post-depositional mixing through slow creep or freeze-thaw cycles may also be responsible for the distribution observed. Therefore, caution must be employed when interpreting ages to account for incorporation of older or younger grains and changes in post-deposition dose rate.

The use of statistical bootstrapping using the CAM is considered a robust representation of palaeodose where bleaching of quartz is sufficient. Errors associated with the CAM are disproportionately high given the reproducibility of D_es demonstrated, therefore, 1σ errors calculated from the boot-strapped D_es are considered to represent the most significant variance of the palaeodose. Statistical bootstrapping using MAM-3 where samples show evidence of heterogeneous bleaching was a useful way of identifying and removing statistically young outliers from the dataset to improve the reliability of palaeodose estimation. It may serve as an alternative to using the finite mixture model for samples containing low dose outliers (Rodnight et al., 2006).

To summarise, the potential for sufficient bleaching of quartz is a function of the mode of sediment transport and deposition and post-deposition sedimentary history. In this respect drowned landscapes should be treated no differently to their terrestrial counterparts when considering bleaching regime.

5.5.2 OSL sensitivity of quartz

Changes in OSL sensitivity after heating, bleaching or irradiation during laboratory experiments (Murray et al., 1995; Murray and Wintle, 2000; Wintle and Murray, 2006) were not observed. This allows OSL sensitivity to be discussed in relation to primary rock type (Sawakuchi et al., 2011) and sedimentary processes (Stokes et al., 2001; Pietsch et al., 2008; Lü and Sun, 2011).

Sediment transport to the continental shelf in the eastern English Channel during periods of lowered sea level is facilitated by the large palaeovalley network that drains parts of both, the British and European continental landmass. As a result, quartz sourced from the British Isles, Southern North Sea, the Rhine-Meuse system and even Alpine hinterlands contribute to the sedimentary composition of English Channel continental shelf deposits.

Consequently, a wide range of quartz properties as a function of provenance is expected and is invoked to explain the range of intrinsic sensitivities displayed by samples from the eastern English Channel. In addition, sedimentary processes operating over glacial to interglacial sea-level cycles likely affect OSL sensitivity. Fluvial incision and marine planation of the underlying Cretaceous bedrock (Weald Clay and Greensand) potentially add relatively immature, low sensitivity quartz to the sediments. Transport of sediments through the palaeovalley network in the eastern English Channel may have improved the sensitivity of the quartz as is demonstrated by Pietsch et al. (2008).

Long-term changes in sedimentary history on ice-proximal continental shelves results in the deposition of quartz of mixed provenance, maturity and transport processes. Despite this, our results show that quartz of sufficient sensitivity can be targeted with suitable experimental design to enable reliable age estimation.

5.5.3 Dose rate in drowned landscapes

Post-depositional mixing of sediments in periglacial settings may have resulted in variable dose rates, introducing uncertainty that is not accounted for in the age calculation (Hülle et al., 2009; Arnold and Roberts, 2011). Preservation of sedimentary structures is a useful indicator of limited post-depositional sediment mixing (Bateman, 2008) and in the case of the eastern English Channel, poor stratification of sediment suggests post-depositional mixing cannot be ignored and incorporation of younger or older grains into the deposit must be considered.

The contribution of cosmic dose to deposits post-submergence is minor due to attenuation of cosmic rays through seawater. However, given the low environmental dose rates received by most samples, an approximation of cosmic dose history using available sea level and stratigraphic information was attempted. Cosmic dose modelling is an iterative process that uses initial age estimations to inform the duration of burial and submergence depending on sample elevation and sea-level history, therefore any uncertainty with initial age estimates will propagate into the model. Despite this, the proposed methodology is considered to give the best estimates given the complicated depositional and post-depositional history of drowned landscapes.

Reconstructing the history of water content to account for attenuation of environmental dose rate is difficult across the full range of landscapes where optical dating has been applied. Drowned landscapes have a slight advantage over terrestrial examples in that they

Depositional Environment	Depositional and post-depositional considerations: Bleaching	OSL sensitivity	Dose rate	Age
Shoreface (young)	Well bleached, deposition in shallow water	All samples demonstrate a range of intrinsic sensitivities with a sufficient number of grains giving light to enable reliable age estimates	*	LV401: 7.8±0.2 ka
Shoreface (old)			*Complicated dose history due to repeated exposure and submergence over sea-level cycles	LV452: 107.8±5.2 ka
Washover fan	Poorly bleached due to rapid erosion and deposition during storm events		*	LV407: 5.3±0.5 ka
Nearshore beach				LV408: 8.0±0.6 ka
Bar	Well bleached due to deposition on bar in a shallow, coarse grained, laterally migrating channel		*	LV402: 17.1±0.8 ka LV403: 15.8±0.9 ka LV411: 16.8±0.7 ka
Periglacial slope	Well bleached component from wind-blown source. Potential sediment mixing through freeze-thaw cycles.		* potential changes in dose rate due to post depositional mixing	LV451: 17.9±0.7 ka

* Dose-rate variability due to changes in water content prior to submergence

Table 5.4: Considerations for assessing the reliability of optical ages for samples from the eastern English Channel. Fot further details see section 5.5 in the main text.

have been flooded by the sea for considerable periods of time, therefore changes in water content post-deposition are expected to be minimal. However, estimating water content during deposition and burial is more difficult and uncertainties can have a significant effect on resultant ages.

In terrestrial and fluvial environments, under cold climate conditions, variabilities would be expected to be greater than those associated with shallow marine and coastal environments due to increased susceptibility to wetting-drying and freeze-thaw cycles. Coastal and shallow marine deposits on tidally influenced coasts are predisposed to changes in water content over twice daily cycles. Despite this, uncertainties are considered to be within ±4% as demonstrated by Roberts and Plater (2007). Reconstructing changes in water content for sediments that have been repeatedly exposed and submerged over glacial to interglacial cycles is more complicated. In these cases, for higher equivalent doses with larger uncertainties, attenuation due to changes in water content over shorter timescales is considered negligible and is taken into consideration within ± 5% uncertainty.

For many submerged sediments, modern water content can be considered the best approximation of past water content and has been used in this case to calculate ages. A comparison between measured water contents from coastal and shoreface sediments in the eastern English Channel (this paper) and shoreface sediments at Dungeness (Roberts and Plater, 2007) has demonstrated the magnitude of variability between water contents from similar depositional settings. If a moisture content of 25±5%, after Roberts and Plater (2007), was used to calculate ages in the eastern English Channel, resultant ages would be increased by a factor of 0.1. These differences in measured water content between eastern English Channel and Dungeness sediments may be explained by: (i) differences in coring processes (English Channel vibrocoring where water may be removed versus Dungeness percussion coring, where water may be maintained or added during the coring process), and/or; (ii) variations in sediment composition (free draining of sediments in eastern English Channel due to higher gravel component). This demonstrates the difficulties for determining water content and highlights that caution must be employed when inferring past water content from modern measured water contents.

5.6 CONCLUSIONS

Quartz extracted from sediments across a range of depositional landforms that are now preserved on the continental shelf in the eastern English Channel are sufficiently bleached and luminescent sensitive to enable reliable estimates of equivalent dose. Resultant ages are remarkably consistent with the proposed stratigraphic model demonstrating the successful application of optical dating to drowned landscapes. Bleaching regime varies across the full range of depositional setting and is not necessarily predictable. Consideration of sedimentary history is vital for assessing the reliability of ages, and in the case of drowned landscapes, interpretation of high resolution geophysical data, where available, can support interpretations - providing considerably more information than is often available in sub-aerially exposed landscapes. Optical dating has proven its worth in unravelling the history of a variety of drowned landscapes, thus providing a chronological control for linking palaeoenvironmental history to changes in climate and sea level across the shallow marine to terrestrial continuum, during the late Quaternary.

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Chapter 6

Landscape degradation of the continental shelf between Britain and France at the glacial-interglacial timescale

Abstract

The erosional morphology of the seabed in the eastern English Channel, in particular the bedrock bedforms within a large palaeovalley (the Northern Palaeovalley), are commonly considered to have formed due to catastrophic flooding through the Straits of Dover during the mid-Quaternary. Thus far interpretations have been based on seabed bathymetric data alone and have not considered the stratigraphic record. Further, the timing of erosion has not been constrained due to an absence of chronometric data. Here, through the integration of multibeam bathymetry and shallow sub-bottom 2D seismic reflection profiles calibrated with vibrocore records, the first straigraphic model of erosion and deposition on the eastern English Channel continental shelf is presented. Published Optical Stimulated Luminescence (OSL) and ^{14}C dates were used to chronmetrically constrain the stratigraphy and allow correlation of the continental shelf record with major climatic/sea-level periods. Five major erosion surfaces overlain by discrete sediment packages have been identified. The continental shelf in the eastern English Channel preserves a record of processes operating from Marine Isotope Stage (MIS) 6 to MIS 1. Planar and channelised erosion surfaces were formed by fluvial incision during relative sea-level fall or lowstand. The depth and lateral extent of incision was partly conditioned by underlying geology (rock type and tectonic structure), climatic conditions and changes in water and sediment discharge coupled to ice sheet dynamics and the drainage configuration of major rivers in Northwest Europe. Evidence for major erosion during or prior to MIS 6 is preserved. Fluvial sediments of MIS 2 age were discovered within the Northern Palaeovalley, providing evidence to suggest the seabed morphology was not solely created by catastrophic flooding but was at least modified by normal fluvial regimes. Discrete sediment bodies are limited to palaeovalley fills or relict Holocene coastal landscapes. Seismic and sedimentary facies

indicate deposition predominantly occurred during transgression when accommodation was created in palaeovalleys. Sediment reworking over multiple sea-level cycles (Saalian-Eemian-early Weichselian) by fluvial, coastal and marine processes created a multi-lateral, multi-story succession of palaeovalley-fills that are preserved as a strath terrace. The data presented here reveal a composite erosional and depositional record that has undergone high degrees of reworking over multiple sea-level cycles leading to a bias towards the preservation of sediments associated with the most recent glacial-interglacial period. It is demonstrated that integration of a variety of techniques at the basin-scale is required to enable reliable reconstructions of palaeogeography and to understand the timing and nature of sedimentary processes in continental shelf settings.

6.1 INTRODUCTION

Significant changes in sea level, a characteristic of the Quaternary period, repeatedly submerge and expose shallow continental shelves making them susceptible to erosion, reworking and deposition, by sedimentary processes operating in terrestrial, marine, and transitional environments. Consequently, the preservation of ancient landscapes on the seabed of the continental shelf provides archives of palaeoenvironmental change (Fedje and Josenhans, 2000; Fitch et al., 2005; Gaffney et al., 2007; Kelley et al., 2010; Hijma et al., 2012), often from time periods poorly represented on land (Mellett et al., 2012a). These drowned landscapes are ideal for examining the interactions between sedimentary processes over glacial-interglacial sea-level cycles, and the factors that determine the imprint they leave (both erosional and depositional) on the continental shelf. The number and detail of case studies is growing rapidly due to recent advances in submarine technologies and increasing availability of commercially acquired data, thus greatly improving our understanding of submarine landscape evolution. These advances are providing crucial evidence for assessing the impacts of future sea-level rise on coastal economies and ecosystems.

The English Channel continental shelf has received attention in the literature for many years (see Gibbard and Lautridou, 2003; Preece, 1995 for reviews, and Dingwall, 1975; Kellaway et al., 1975; Roep et al., 1975; Smith, 1985, 1989; Gibbard et al., 1988; Gibbard, 2007; Gupta et al., 2007; Toucanne et al., 2009a) because of its potential to preserve a record of the timing and mechanism that led to isolation of Britain, as a geographical island, from the European continent during the mid-Quaternary. Despite ongoing debates regarding the timing of erosion (Meijer and Preece, 1995; van Vliet-Lanoë et al., 2000;

Busschers et al., 2008; Hijma et al., 2012), the most recent evidence supports an Marine Isotope Stage (MIS) 12 age, at least for initial breach (Toucanne et al., 2009a), with an English Channel-North Sea marine connection during highstand, at some point between MIS 12 to MIS 6 (Meijer and Cleveringa, 2009). The resulting palaeogeographical configuration of Britain and Northwest Europe has implications for the migration of flora and fauna (Preece, 1995; Meijer and Cleveringa, 2009) including hominins (Stringer, 2006; Hijma et al., 2012) throughout the Pleistocene. Additionally, reorganisation of drainage basins and funnelling of freshwater discharge through the English Channel during cold stages as a consequence of breaching of the Straits of Dover (Gibbard et al., 1988; Bridgland et al., 1993; Bridgland and D'Olier, 1995; Gibbard, 1995; Busschers et al., 2007; Toucanne et al., 2009a), may have contributed to destabilisation of the Atlantic thermohaline circulation (Menot et al., 2006; Gibbard, 2007; Toucanne et al., 2009b; 2010).

A number of mechanisms have been proposed to explain breaching at the Straits of Dover including gradual erosion as a result of fluvial down-cutting (Dingwall, 1975; Gibbard et al., 1988; Busschers et al., 2008) and catastrophic flooding (Smith, 1985; Gibbard, 2007; Gupta et al., 2007). The bedrock morphology of the continental shelf in the eastern English Channel, particularly the erosional bedrock bedforms preserved in the Northern Palaeovalley, have been interpreted as the product of high magnitude flows linked to erosion at the Straits of Dover by megaflood events (Gupta et al., 2007). However, this interpretation was based on bathymetric data of the seabed only, and did not consider the sedimentary record preserved in the subsurface. Distinguishing catastrophic events from ‘normal’ sedimentary processes requires an understanding of how fluvial and marine processes, over multiple sea-level cycles, interact to create the morphological and sedimentary history of the continental shelf.

Here, the first detailed chronometrically constrained stratigraphic record of palaeoenvironmental change on the eastern English Channel continental shelf is presented. The erosional and depositional record is established through the integration of multi-beam bathymetric data with subsurface geophysical and vibrocore data. This permits reconstructions of palaeogeographic- and drainage configurations during time periods for which a chronology has been obtained. Catastrophic flood events are discussed in light of new insights into the timing and nature of erosion and deposition on the continental shelf.

6.2 GEOGRAPHICAL AND GEOLOGICAL SETTING

The English Channel, or La Manche, is a narrow seaway that during sea-level highstands separates southern Britain from northern France. The narrowest and shallowest tract is at the Straits of Dover and widest and deepest tract is between Cornwall and Brittany in the west. Overall, the continental shelf submerged beneath the English Channel is a gently dipping slope (ca. 0.01°) that extends 600 km westwards from the Straits of Dover towards the continental shelf edge break in water depths of -200 m Ordnance Datum (OD) (Pantin and Evans, 1984). In the north-east, this slope is dissected by a complicated network of palaeovalleys that locally form offshore extensions of contemporary rivers such as the Seine, Somme and Solent (Lercolais, 1997; Velegrakis et al., 1999; Bridgland, 2002; Antoine et al., 2003; Lericolais et al., 2003; Tessier et al., 2010;) (Fig. 6.1). These palaeovalleys are tributaries of a major axial fluvial system (Channel River/Fleuve Manche) that channelled discharge from the Thames and Rhine-Meuse rivers (Gibbard et al., 1988; Lercolais, 1997) along with meltwater from Northwest European Ice Masses (Toucanne et al., 2009b, 2010) during late Quaternary sea-level lowstands. Large palaeovalleys of the Channel River not linked to present day drainage networks include the Lobourg Channel in the Straits of Dover, the Northern Palaeovalley in the eastern English Channel and the Median Palaeovalley in the central Channel basin (Fig. 6.1). The course of the Channel River to the shelf edge break is interrupted by the Hurd Deep, a NE-SW trending linear depression of Neogene tectonic origin that acted as a sediment sink when the shelf was exposed during sea-level lowstands (Lericolais et al., 1996).

The area referred to in this paper as the eastern English Channel represents ca. 5000 km^2 of the seabed offshore of the south-east coast of England (Fig. 6.1). The extent of this study area is delimited by the availability of geophysical data (Fig. 6.2). Seabed morphology reveals a number of E-W to NE-SW trending confined topographic lows, one of which includes the Northern Palaeovalley. This morphology is the seabed expression of a network of palaeovalleys that physically connect the Lobourg Channel to the Northern Palaeovalley and the Median Palaeovalley (Fig. 6.1).

The geology of the eastern English Channel is dominated by Cretaceous strata of the Weald Artois anticline and Tertiary deposits of Hampshire-Dieppe basin (Hamblin et al., 1992). A general WSW-ENE alignment of fold and fault structures is apparent. The eastern English Channel as a geological province has remained relatively stable since uplift of the Weald-Artois anticline and sedimentation in the Hampshire-Dieppe basin in response to a late

Alpine compressional phase during the Miocene (Woodcock and Strachan, 2000). Thus, Pliocene and Pleistocene evolution can mostly be attributed to fluvial response to long-term tectonics and higher frequency relative sea-level changes (Lagarde et al., 2003; Roy et al., 2011). Gradual uplift of the English Channel during the Quaternary is recorded in fluvial terrace staircases of major rivers draining southern Britain and northern France (Antoine et al., 2000, 2007; Briant et al., 2006; Westaway et al., 2006) and raised beaches of the south coast of England (Preece et al., 1990; Bates et al., 2003; Westaway et al., 2006; Bates et al., 2010). It is likely that uplift and subsidence in response to glacio-isostasy over glacial-interglacial cycles (Lambeck, 1997; Shennan et al., 2000; Waller and Long, 2003; Busschers et al., 2008) influenced development in the eastern English Channel.

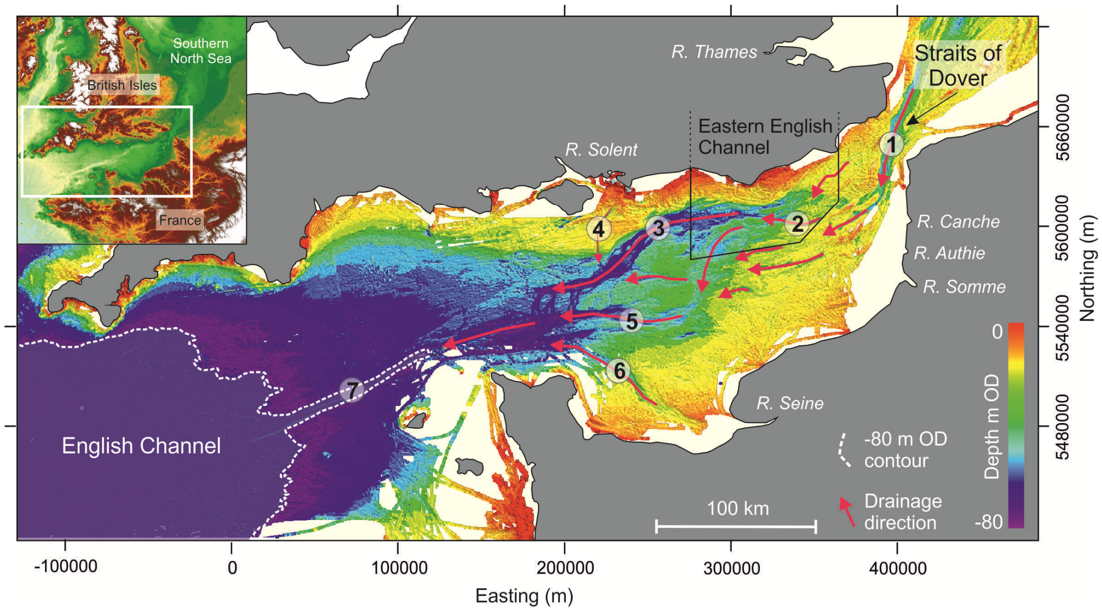


Figure 6.1: Seabed bathymetry of the English Channel continental shelf. Inset map shows merged bathymetric and topographic data for Northwest Europe (Bathymetry: The GEBCO_08 Grid, version 20091120, http://www.gebco.net. Digital elevation data: SRTM (Jarvis et al., 2008) available from http://srtm.csi.cgiar.org). Bathymetry source for main map is Olex, used with permission of Olex AS. Depths are relative to UK mean sea-level (OD). Arrows indicate major drainage configurations and numbers identify offshore extensions of large European rivers and main palaeovalleys/topographic features: (1) Lobourg Channel, (2) South Basserelle (SB) Palaeovalley, (3) Northern Palaeovalley, (4) Palaeo-Solent, (5) Median Palaeovalley (Antoine et al., 2003), (6) Palaeo-Seine, (7) Hurd Deep. Coordinate system WGS84 UTM Zn 31N.

In the eastern English Channel study area up to 70% of the seabed is characterised as bedrock exposed at the seabed or bedrock covered by a thin (<1 m) veneer of sediment (James et al., 2011). Significant thicknesses (up to 30 m) of sediment are limited to infilled portions of palaeovalleys and a small number of constructional bedforms (Hamblin et al., 1992). Sediments are predominately siliclastic, comprising sand and gravel. Fine grained and organic-rich sediments are rare and limited to drowned palaeovalleys (Bellamy, 1995; Velegrakis et al., 1999; Gupta et al., 2004) or back barrier-settings (Mellett et al., 2012a), proximal to the present-day coastline.

6.3 METHODS

6.3.1 Bathymetric data collection and processing

To determine the depth to seabed relative to Ordnance Datum (OD) i.e. the British reference altitude of mean sea level at Newlyn, a range of bathymetric data sources were used, depending on the resolution required. Single-beam and multi-beam echo soundings were collected simultaneously with seismic reflection data (see section 6.3.2 and Fig. 6.2 for survey track lines). The bathymetric data are used to calibrate seabed response from seismic reflection profiles to OD. SeaZone Solutions Ltd. digital bathymetry and digital charted bathymetry were obtained and interpolated using a standard Kriging algorithm in ArcGIS into a 120 m cell size grid. This allowed the morphology of the seabed to be assessed and provided a local surface to which all other interpolations could be tied. The Olex global bathymetry database (www.olex.no) was used to characterise regional bathymetry outside the study area (Fig. 6.1). These data were collected using standard single-beam echo sounders and GPSs. Data coverage in the English Channel is exceptional producing a high resolution chart (between 20 m and 200 m track spacing) of the seabed. Positioning accuracy is generally <10 m and vertical resolution in water depths of <100 m is 0.1 m (Bradwell et al., 2008).

6.3.2 Seismic data acquisition and interpretation

Shallow sub-bottom, 2D seismic reflection data were collected over 20 years of prospecting surveys by the Resource Management Association (RMA, comprising CEMEX UK Marine Ltd., Hanson Aggregates Marine Ltd. and Tarmac Marine Dredging Ltd.), and made available for this study. These seismic data were collected using surface-towed Boomer sources typically operating at frequencies between 0.5-5 kHz that penetrate and resolve unconsolidated sediments to ca. 50 m below the seabed. These data were collated with 2D seismic reflection data collected by the Centre for Environment, Fisheries and Aquaculture Science (CEFAS) and the British Geological Survey (BGS) as part of the Eastern English Channel Marine Habitat Map Project (James et al., 2007). Additional shallow sub-bottom seismic reflection data (Boomer 1-4 kHz) were collected as part of this study to permit integration and correlation between individual surveys and improve spatial resolution where data coverage was sparse. Through the integration of all datasets a total of 6000-line km of seismic reflection data were used to assess the nature, extent and thickness of sediments preserved in the eastern English Channel. The location of all survey data are presented on Figure 6.2.

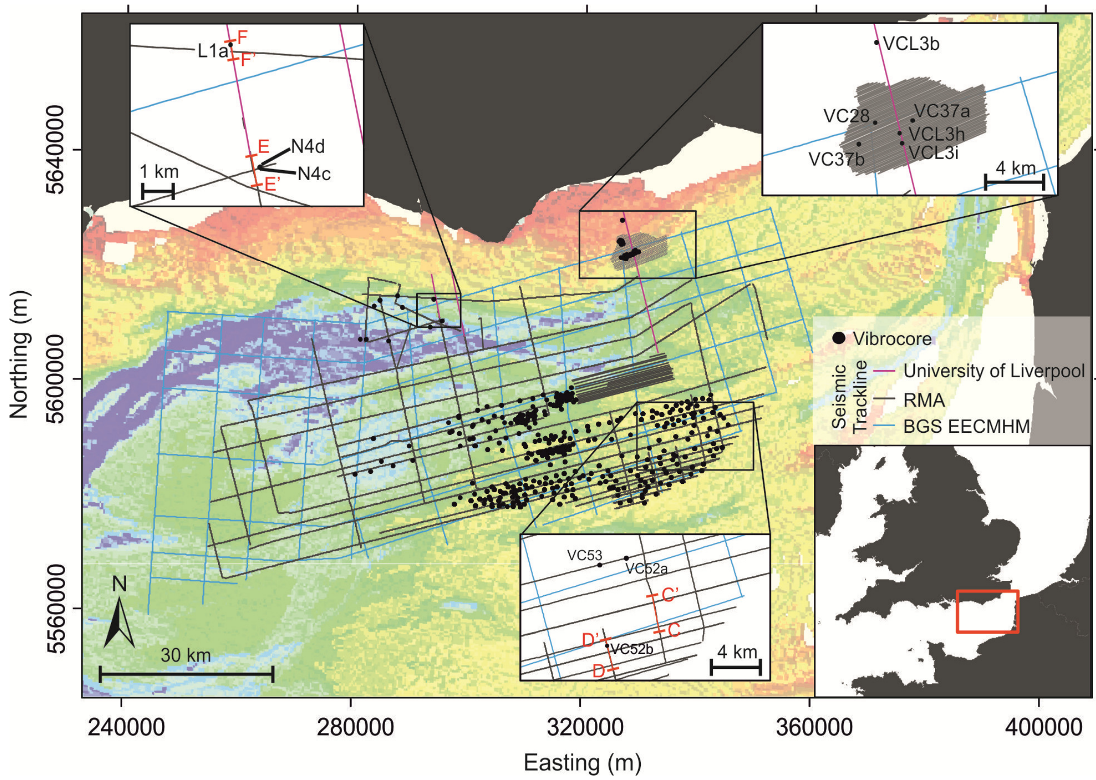


Figure 6.2: Offshore seismic and vibrocore data. Bathymety is Olex, used with permission of Olex AS. Enlarged inset maps show the location of seismic profiles presented in Figures 6.4, 6.5 and 6.6, and the positioning of vibrocores referred to in Figures 6.10 and 6.11, and Table 6.3. Map coordinates WGS84 UTM Zn 31N.

Interpretation of seismic reflection profiles is based on Mitchum et al. (1977). Characterisation of seismic facies and seismic stratigraphy was carried out according to the criteria presented in Figure 6.3. A summary of all seismic facies is presented in Table 6.1 and shown together with interpreted seismic lines in Figures 6.4, 6.5 and 6.6. In unconsolidated sediments, an acoustic velocity of 1700 ms^{-1} was used to convert two-way travel time (TWTT) to depth in metres.

Seismic facies	Internal geometry	Frequency	Amplitude	Continuity	Reflector configuration	Reflector termination
sf_1	Sheet	Medium to high	High	Continuous	Parallel - low angle parallel oblique	Onlap
sf_2	Channel	Medium to low	High	Continuous	Parallel draped	Concordance
sf_3	Channel or lens	medium	High	Continuous to discontinuous	Sub-parallel	Onlap
sf_4	Channel or lens	Medium to low	Medium to high	Continuous to discontinuous	Oblique to sigmoid	Downlap and truncation
sf_5	Lens	Medium	Medium to high	Continuous	Parallel oblique	Downlap and truncation
sf_6	Channel	Medium-high	medium	Discontinuous	Oblique to hummocky	Downlap and truncation
sf_7	Channel	Medium	Medium to low	Discontinuous	Hummocky to chaotic	-
sf_8	Channel	Medium to low	Low	Discontinuous	Un-differentiated	-
sf_9	Mound	Medium	Medium to high	Discontinuous	Oblique to sigmoid	Downlap and truncation
sf_{10}	Drape	Reflectors below resolution of unit				

Table 6.1: Seismic facies characteristics. Refer to Figure 6.3 for a guide to the interpretation of reflector configurations and facies geometries.

6.3.3 Identification of erosion surfaces

To determine the morphology of the unconformity separating bedrock from unconsolidated sediments, an isopach of sediment thickness (Fig. 6.7b) was subtracted from seabed bathymetry (Fig. 6.7a) to produce a map showing depth to bedrock relative to OD (Fig. 6.7c). Sediment thickness (from seabed to bedrock unconformity) was measured on individual seismic lines and interpolated into a 3D grid using Kriging (300 m cell size) in ArcGIS (Fig. 6.7b). This resulting volume was subtracted from bathymetric data using spatial analyst in ArcGIS. Spatial limitations of available seismic data meant this could only be carried out within a limited area referred to herein as the interpolated grid. Identification of discrete erosion surfaces within the interpolated grid was achieved by producing a frequency histogram of bedrock elevations and distinguishing between multiple populations (Fig. 6.8a). The erosion surfaces were analysed to identify key morphological features (Fig. 6.8b and 6.9). James et al. (2011) identify areas where bedrock is exposed at seabed (Fig. 6.8c) which was used to provide some information on the morphology the bedrock unconformity outside the interpolated grid.

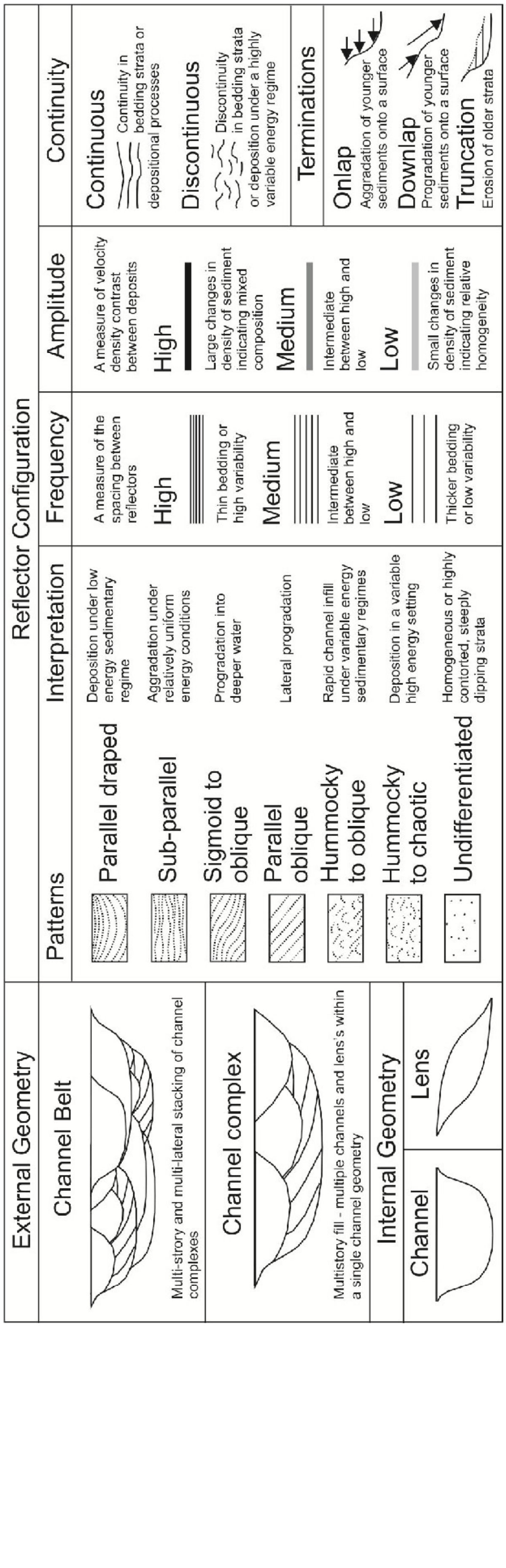


Figure 6.3: Guide to the interpretation of seismic reflection data based on Mitchum et al. (1977).

6.3.4 Vibrocoring and sedimentary facies

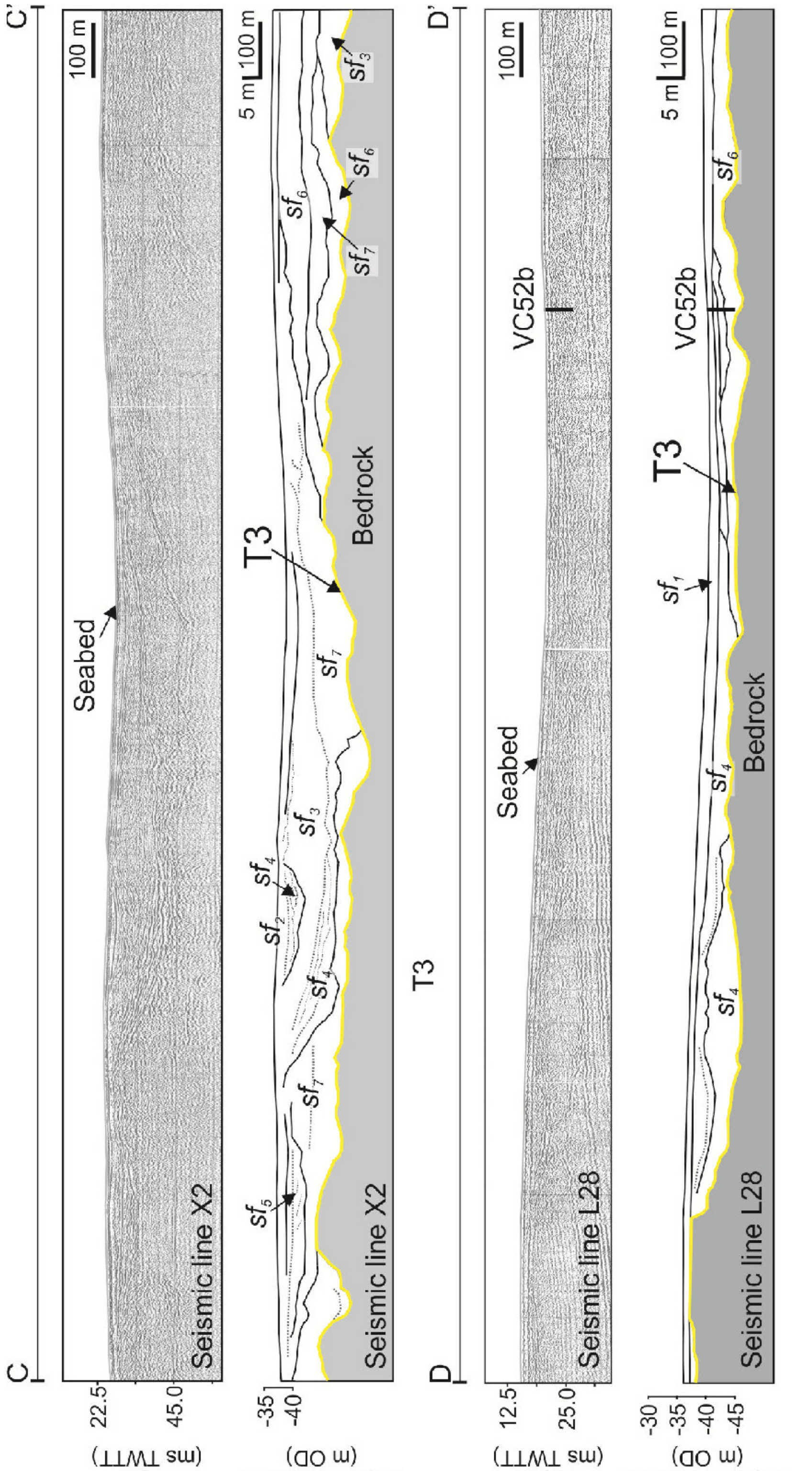
A database containing over 300 vibrocores tied to seismic reflection profiles was made available by the RMA. This database included core descriptions logged in accordance with BS5930 (1981), core photographs and the results of particle size distribution analysis carried out at the discretion of the RMA within each core. All cores were recovered with a high-powered vibrocorer (6 m maximum penetration) over a series of individual surveys that corresponded with the collection of seismic reflection data. Sub-samples of these cores were selected to allow higher resolution sedimentological descriptions and sampling for lithological and chronometric analyses. An additional 11 vibrocores were collected during March 2010 to supplement the core database, to calibrate seismic facies with sedimentary facies, and obtain to samples for chronometric analysis. The locations of vibrocores are indicated on Figure 6.2. Data obtained from the core database and vibrocore samples form the basis for lithostratigraphic analysis and characterisation of sedimentary facies. A summary of all sedimentary facies is presented in Table 6.2 and representative core photographs are shown in Figures 6.10 and 6.11.

6.3.5 Chronometric data

A total of 9 Optical Stimulated Luminescence (OSL) ages were obtained using sand-sized quartz extracted from a selection of vibrocores. The analyses were carried out at the University of Liverpool Luminescence Dating Laboratory. Full details are given in Mellett et al. (2012b). This chronological information was supplemented by OSL and radiocarbon (^{14}C) ages from sediments deposited in the South Basserelle (SB) palaeovalley (Fig. 6b) reported by Wessex Archaeology (2008). Details of chronometric data are presented in Table 6.3.

6.4 RESULTS

Qualitative analysis of the bedrock unconformity revealed four major erosion surfaces referred to as T2, T3, T4 and maximum (deepest) erosion (ME) surface (-67 m OD) (Fig. 6.8a). An additional erosion surface (T1) is characterised according to seabed elevations outside of the interpolated grid where bedrock is exposed at seabed (Fig. 6.8c). A framework for establishing the relative stratigraphy of erosion surfaces assumes denudation through time in an area of overall tectonic uplift (Davis, 1899). This implies surface T1 is the oldest surface at highest elevations and ME is the youngest base level of the most recent erosional regime prior to submergence of the continental shelf by post-glacial sea-level rise. Erosion surfaces and depositional facies are discussed in chronological order from oldest to youngest.



igure 6.4: seismic reflection profile and interpreted panels illustrating seismic facies character and association for deposits verlying surface T3. The location of profiles C-C' and D-D' are highlighted on Fig. 6.2. A sedimentary log of VC52b is shown n Fig. 6.11.

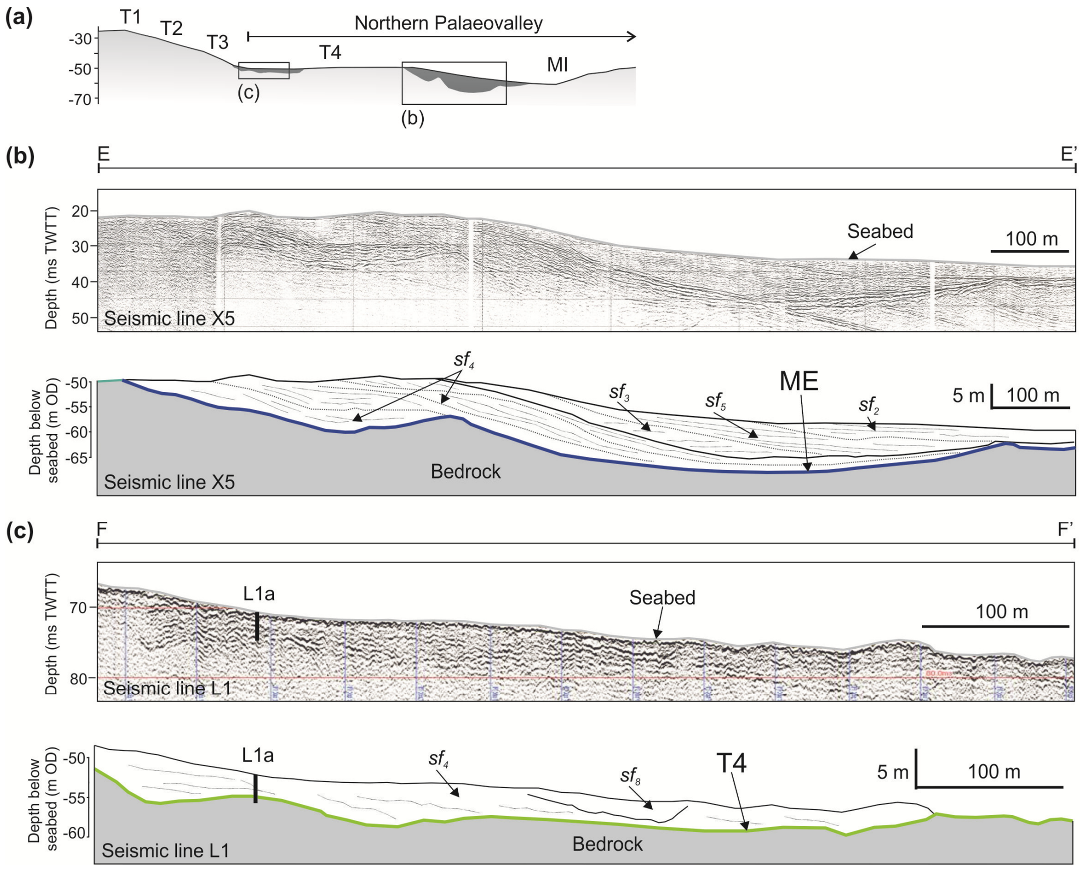


*Figure 6.5: **(a)** Cross-profile showing bathymetry of the seabed and the location of deposits overlying surfaces T4 and ME. **(b)** Seismic reflection profile and interpreted panels illustrating seismic facies character and association for deposits overlying surface ME. The location of profile E-E' is highlighted on Figure 6.2. **(c)** Seismic reflection profile and interpreted panels illustrating seismic facies character and association for deposits overlying surface T4. The location of profile F-F' is highlighted on Figure 6.2. A sedimentary log of vibrocore L1a is presented in Figure 6.11.*

6.4.1 Bedrock erosion

Erosion surface T1 lies outside of the interpolated grid and occupies elevations between 0 m to -30 m OD (Fig. 6.8c). The erosion surface dips at 0.1° towards the south and slopes gently (0.02°) westwards towards the continental shelf break (Fig. 6.8c).

Erosion surface T2 lies within the interpolated grid at elevations between -30 m OD and -38 m OD. Outside of the interpolated grid, bedrock is exposed at seabed at these elevations implying surface T2 is present to the NE of the interpolated grid where it appears as a planar topographic platform (Fig. 6.8c).

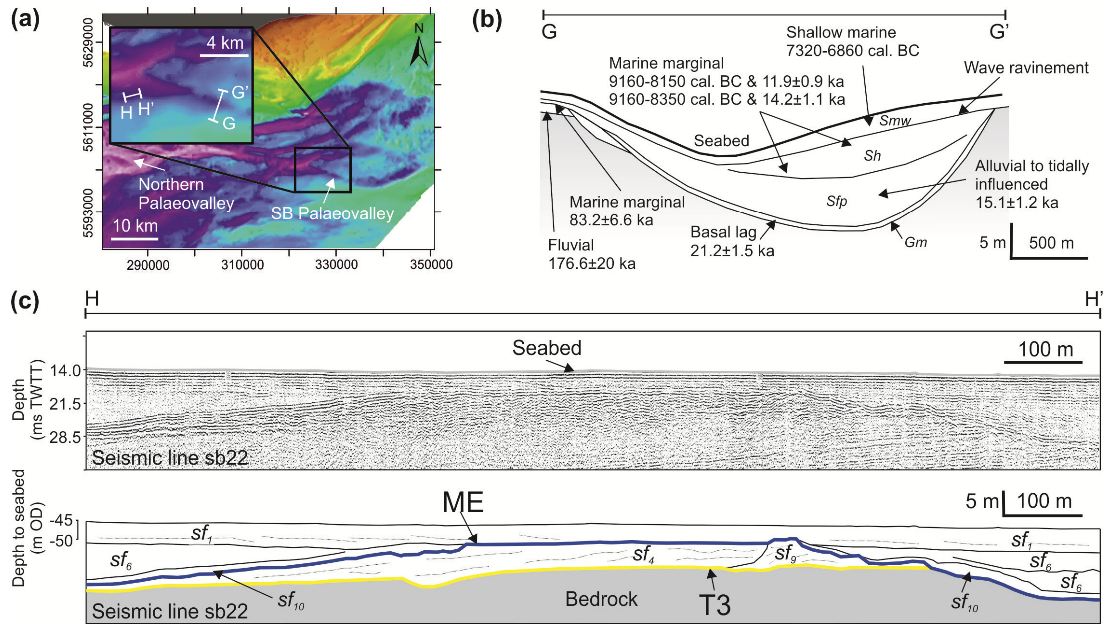


Figure 6.6. ***(a)*** *Bathymetry in the eastern English Channel showing the morphology of the SB Palaeovalley as it becomes confluent with the Northern Palaeovalley. Bathymetry © British Crown and SeaZone Solutions Limited. All rights reserved. Product license No. 112010.009. Bathymetry is shaded according to the scale given in Fig. 6.7a. Locations of cross-profiles G-G' and H-H' are shown as white lines.* ***(b)*** *Schematic representation showing the stratigraphy and depositional context of sediments preserved within the SB Palaeovalley adapted from Wessex Archaeology (2008). Sedimentary facies are given in italics. Age information obtained from samples representing each stratigraphic unit are presented. Full details of these ages are given in Table 6.3. OSL ages are given in ka and ^{14}C ages in cal. yrs BC. For marine marginal sediments, a single sample was extracted for OSL and ^{14}C was carried out on shell material contained within that sample.* ***(c)*** *Seismic reflection profile and interpreted panel illustrating seismic facies character and association for deposits overlying surface T3 and ME.*

Surface T3 is the most widespread surface within the interpolated grid and it displays a strong degree of continuity at elevations between -38 m and -47 m. As a whole it is characterised by a relatively planar gently dipping (ca. 0.05° westwards) continuous platform (Fig. 6.8c). Cut into this surface is a network of cross-cutting bedrock channels with planform geometries ranging from low sinuosity linear channels to a meander cut-off indicative of higher degrees of sinuosity (Fig. 6.9). Surface T3 only occurs on strata of the Hampshire Dieppe basin. The low angle, but well defined slope (0.5° to 3.0°) that separates this surface from surfaces T1 and T2 has been defined as the margin of the Northern

Palaeovalley (Smith, 1985; 1989; Hamblin et al., 1992; Antoine et al., 2003; Gupta et al., 2007).

Surface T4 occupies elevations between -47 m and – 58 m, and in the NE forms the base of WSW-ENE trending, parallel aligned, channels (on average 15 km length and 1.5 km width) that subdivide surface T3 into elongate bedrock islands (Fig. 6.9b). To the SW, surface T4 broadens into a 20 km-wide depression (Fig. 6.9) that is part of a large SW-NE trending palaeovalley that extends westwards towards the Hurd Deep (Fig. 6.1).

The base of the maximum erosion (ME) surface is planar at -67 m OD. It is incised into surface T4 and creates a confined channel (the SB Palaeovalley Fig. 6.9a) that widens towards the west to form the base of the Northern Palaeovalley (Fig. 6.9a). The SB Palaeovalley follows structural folds in the bedrock geology, incising into and running parallel with London Clay at its contact with underlying chalk until it reaches Eocene-aged stratigraphy exposed in the base of the Northern Palaeovalley. Within the Northern Palaeovalley, isolated remnants of T4 form a collection of streamlined bedrock islands (Fig. 6.9a).

6.4.2 Depositional facies and environments

Deposits on surfaces T1 and T2

Bedrock is exposed at the seabed across large areas of surface T1 (Fig. 6.8c). The thickest sediment cover is observed in the northeast around Hastings Bank and Rye Bay (Fig. 6.8c). Depositional architecture and geomorphic change in the Hastings Bank area are addressed in Mellett et al., (2012a). In summary, a seaward-thickening wedge has been identified comprising sand overlain by coarse grained gravel ridges that are breached by finer grained silty deposits. The entire succession has been interpreted as a submerged barrier complex of Holocene age. Other deposits in the Rye Bay have been characterised as a seaward prograding shelf sand body with a minor coarse clastic component (Dix et al., 1998). Elsewhere on surface T1, sediment is confined to the fills of palaeovalleys that drained the southern British uplands (Bellamy, 1995; Gupta et al., 2004).

Deposition on surface T2 is limited to sandy sediment waves and banks (Fig. 6.7a). These relict sediment banks are inactive under the present-day hydrodynamic regime (Anthony, 2002) but probably represent deposition during the mid- to late Holocene sea-level rise when tidal currents were influential at these depths.

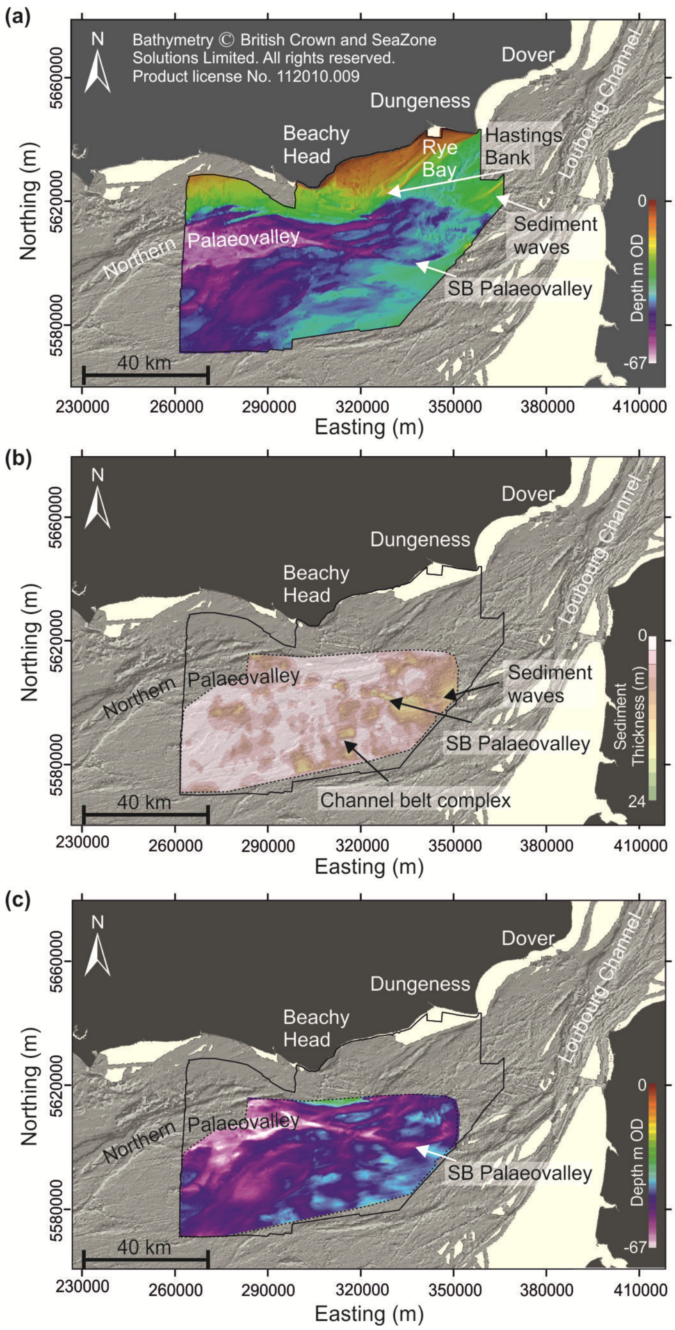


*Figure 6.7: **(a)** Seabed bathymetry of the eastern English Channel study area (© British Crown and SeaZone Solutions Limited. All right reserved. Product license No. 112010.009.), overlying Olex shaded relief data, used with the permission of Olex AS. **(b)** Isopach of sediment thickness overlying Olex shaded relief data, used with permission of Olex AS. Solid black line delimits eastern English Channel study area. Dashed black line delimits interpolated grid. **(c)** Depth to bedrock shown within interpolated grid delimited by dashed black line, overlying Olex shaded relief data, used with permission of Olex AS. Map coordinates WGS84 UTM Zn 31N.*

Deposits on surface T3

Surface T3 is the most extensive surface in the eastern English Channel making a simple classification of associated deposits difficult. The most volumetrically significant sedimentary deposits of the eastern English Channel are associated with this surface and form a sheet of sediment that thins to bedrock in the west and is truncated by erosion surfaces T4 and ME in the north and west. Deposits overlying T3 have a composite and complicated seismic signature comprising multiple discontinuous erosion surfaces overlain by oblique to chaotic reflector patterns (Fig. 6.4). This seismic facies association is interpreted as representing a multi-storey and multi-lateral amalgamated channel belt

(Miall, 2006) (Fig. 6.3). The channel belt extends 30 km to the west and 20 km to the north within the area delimited as the interpolated grid and is on average less than 6 m thick (Fig. 6.7b). Channels incise either (i) directly into bedrock or (ii) through alluvium until bedrock is reached. The characteristic seismic stratigraphic and sedimentary architecture of individual palaeovalleys within the channel belt are shown in Figure 6.4, and full descriptions of seismic and sedimentary facies are given in Tables 6.1 and 6.2.

Identifying single channels can be achieved on N-S trending seismic profiles where channels are intersected at 90° to their longitudinal profile and can be traced down-dip across seismic profiles (Fig. 6.4). Channel margins cut into alluvium with channel thalweg erosion into bedrock. Asymmetric cross-sections of the channel bodies combined with oblique to sigmoid reflector patterns (sf_4) at the channel margins indicate some degree of sinuosity, which is also reflected in the morphology of surface T3 (Fig. 6.9). Assuming channels are intersected perpendicular to flow direction, individual channels are on average between 0.5 and 1.5 km wide.

Sedimentary infill is complex with a number of smaller cut-and-fill cycles confined within the composite channel geometry. Oblique downlapping seismic reflectors (Sf_4) are limited to the steepest margin of the channels suggesting deposition is driven by lateral- and downstream-accretion of bar complexes. Discontinuous, hummocky to chaotic reflectors of Sf_7 (Table 6.1) indicative of contrasting lithologies are present at the base of the channel implying deposition occurred under a variable sedimentary regime. Sub-parallel reflectors of Sf_3 (Table 6.1) representing lateral continuity in lithology, correspond to the latest stages of sedimentary infill and indicate aggradation under a more consistent energy regime.

Association of sedimentary facies with seismic facies is difficult due to the resolution of both seismic and core records that are biased towards superficial strata and thus the later stages of channel infill. Typically, cores reveal gravels supported by a sand matrix (Gm) interbedded with fine grained well-sorted, laminated sands (Sfw) (Table 6.2 and Fig. 6.10). Coarse-grained, flint-rich gravels are most likely the product of local bedrock erosion and later transport by fluvial processes within the channel belt complex. The abundance of shallow marine foraminifera (predominantly *Elphidium sp.* and *Ammonia sp.*) in Sfw indicates deposition in a shoreface setting and these sedimentary facies are considered the product of flooded valley infilling during sea-level rise. The intercalation of fluvial and shallow marine environments is reflected in the amount of reworked thick-walled shells within the coarse grained deposits. Distinguishing between marine reworked fluvial deposits and fluvial reworked marine deposits is problematic but implies deposition occurred in an environment where the position of the shoreline fluctuated in response to sea-level oscillations. In summary, deposits overlying surface T3 are interpreted as a composite sheet of sand and gravel that represent widespread interfingering and reworking by marine and fluvial processes.

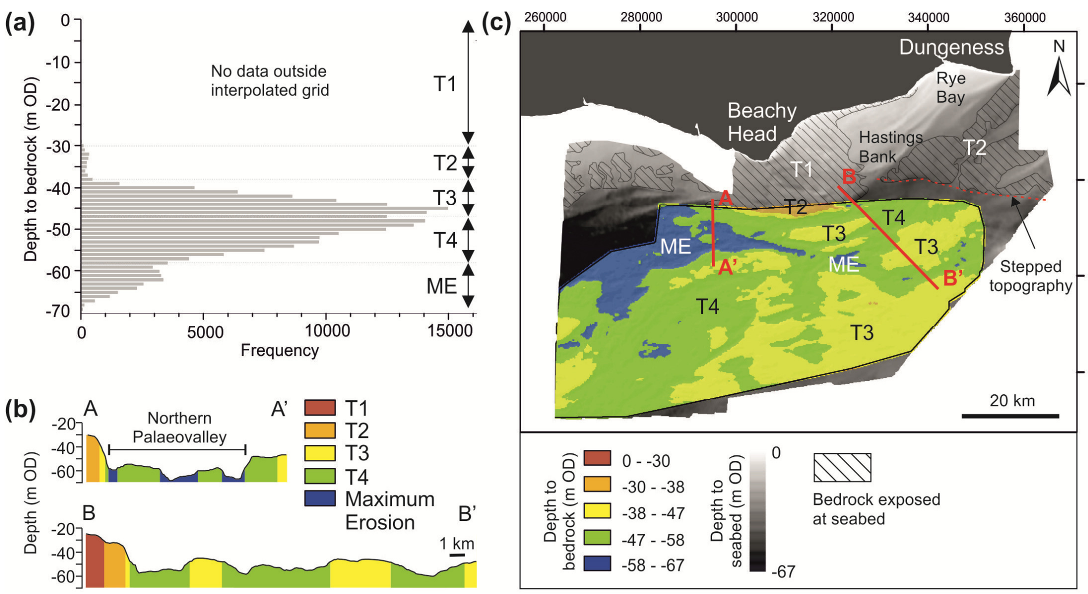


*Figure 6.8: **(a)** Frequency distribution of bedrock elevations showing subdivision of erosion surfaces. **(b)** Cross-sections showing depth to bedrock. Locations of profiles given in Fig. 6.8c. Elevation of erosion surfaces shaded according to the scale in Fig. 6.8c. **(c)** Depth to bedrock shown within interpolated grid, shaded to highlight major erosion surfaces identified in Fig. 6.8a. Outside interpolated grid, depth to seabed is given (© British Crown and SeaZone Solutions Limited. All right reserved. Product license No. 112010.009.). Areas where bedrock is exposed at seabed are taken from James et al., (2011). Map coordinates WGS84 UTM Zn 31N.*

Thinning of deposits overlying surface T3 to the west is attributed to an erosional event as seen from the truncation of seismic reflectors and deposition of sf_1 (Table 6.1 and Fig. 6.4) that is evident on seismic profiles throughout the eastern English Channel. The erosion surface at the base of Sf_1 is interpreted to represent wave ravinement during transgression due to its spatial extent and the planar nature of the lower bounding surface. Parallel onlapping seismic reflectors and the uniform thickness of sedimentary facies Smw and Cm (Table 6.2 and Fig. 6.10) suggest deposition subsequently occurred in a marine environment.

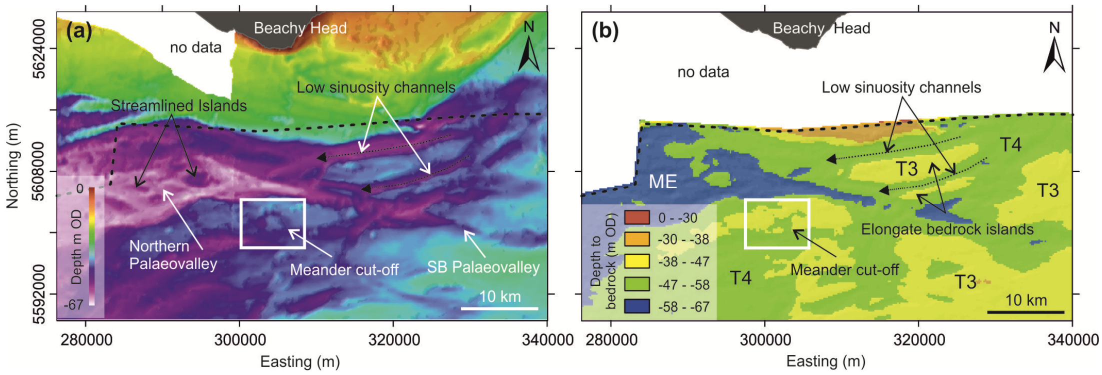


*Figure 6.9: **(a)** Seabed bathymetry highlighting key morphological features (© British Crown and SeaZone Solutions Limited. All right reserved. Product license No. 112010.009.). **(b)** Bedrock surface showing the imprint of seabed morphological features on the underlying bedrock. Dashed black line delimits the extent of the interpolated grid. Map coordinates WGS84 UTM Zn 31N.*

One of the most striking features of the channel belt deposits is variations in colour within sedimentary facies Gm (Table 6.2 and Fig. 6.10). The gravels are clearly heavily weathered and show evidence, based on their colour, of different degrees of secondary iron oxide development (Hurst, 1977). This would suggest that subsequent to deposition, channel belt sediments were sub-aerially exposed for a period of time sufficient enough for the soil to develop a red to dark brown colour prior to erosion by wave ravinement.

Deposits on surfaces T4 and ME

Sediments associated with surface T4 occur in isolated patches and are usually smaller than the spatial resolution of the available data. Seismic Line L1 reveals a small remnant deposit of < 5m in thickness at the base of a slope (1°) separating surface T4 from surface T3 (Fig. 6.5a). This small lens of sediment appears to occupy a minor depression within surface T4 and oblique downlapping reflectors (sf_4) indicate downslope progradation (Fig. 6.5c). Full recovery of vibrocore L1a revealed a very poorly sorted and poorly stratified succession of sandy mud, muddy sand and muddy gravel (Fig. 6.11). The gravel component comprises fine to cobble-size clasts of angular flint and chalk. Coarse grained beds are interbedded with finer grained beds dominated by a clay component. At the base of the core, highly weathered chalk confirmed bedrock was reached. This deposit is interpreted as a remnant of mass wasting at the base of a slope under cold climate conditions (head deposit).

Preservation of sediments associated with the maximum erosion surface is rare and limited

Sedimentary facies	Description	Depositional environment/process
Gm	Very poorly sorted matrix supported sandy gravel. Gravel typically comprises sub-angular to sub-rounded flint clasts. Matrix is medium to coarse sand.	Fluvial
Gfu	Well sorted clast supported coarse gravel up to cobble size. Gravel is largely flint and sub-rounded	Coastal (nearshore)
Sfp	Fine to medium sand with frequent laminations of silty clay. Laminations are generally fine but can be up to 1cm in thickness. Clay is occasionally organic rich.	Alluvial or tidally influenced
Sh	Poorly sorted slightly gravelly fine to medium sand with frequent outsized gravel clasts. Gravel component is sub-angular to sub-rounded, fine to medium size and of various lithologies. Frequent shell fragments throughout.	Shallow marine to coastal (nearshore)
Smw	Generally well sorted occasionally moderately sorted slightly gravelly medium to coarse calcareous sand. Shells, both whole and fragmented are frequent. Occasional organic mottles and inclusions of granule size coal.	Coastal – shallow marine
Sfw	Very well sorted laminated fine to medium size quartz sand. Occasional inclusions of coal of granule size.	Shallow marine (shoreface)
Cd	Very poorly sorted silty sandy gravelly clay. Gravel is largely chalk and flint. Deposit is stiff and varies considerably in composition.	Periglacial slope
Cm	Very poorly sorted matrix supported gravel. Matrix is clayey sandy silt with frequent shell fragments throughout. Gravel is angular to sub-rounded, fine to medium size.	Wave/tide reworking
Br	Bedrock, often highly weathered.	-

Table 6.2: Classification and interpretation of sedimentray facis according to lithological composition.

the Northern Palaeovalley. The extent of these deposits is highlighted in Figure 6.7b and the seismic stratigraphy presented in Figures 6.5 and 6.6.

Sediments within the Northern Palaeovalley are limited to the margins of the main channel (Fig. 6.5a). The characteristic geometry, seismic stratigraphy and lithology of these deposits are shown on Figures 6.5b and 6.11. Sediments partially fill the channel, are thickest at the channel margins, and thin towards the centre of the channel and outer channel banks. Seismic reflector patterns (sf_4) indicate accretion towards the channel thalweg. Recovery of vibrocores was low due to the coarse clastic nature of sediments. Maximum recovery was achieved with N4c and N4d (Fig. 6.11) revealing matrix-supported gravel (Gm) interbedded with laminated silty fine sand (Sfp). Both the geometry of seismic facies and lithology of sediments imply deposition of a point bar within a bedrock fluvial channel. In the example shown in Figure 6.5b at least three phases of accretion can be identified by separation of inclined reflectors by high amplitude reflectors. Within the channel thalweg, a bounding surface delimits the extent of accretion and slightly inclined to parallel onlapping reflectors mark a change in sedimentary regime (sf_2, sf_3 and sf_5) with deposition of finer grained, less variable sediments.

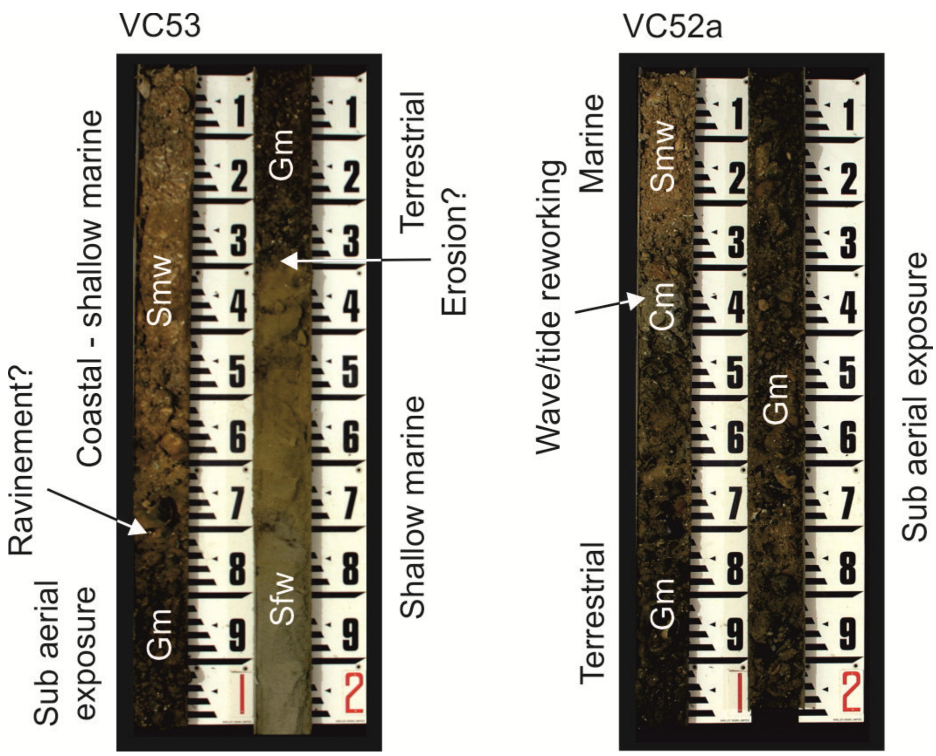


Figure 6.10: Vibrocore photographs showing the composition of sedimentary facies presented in Table 6.2. The locations of vibrocores are given in Figure 6.2.

The SB palaeovalley has a clear bathymetric and seismic expression and can be traced for 45 km in the eastern English Channel (Figure 6.6a). Analysis of sub-bottom seismic profiles revealed a bedrock-confined single channel incised into deposits associated with T3 and infilled with up to 25 m of sediments (Fig. 6.6c). At the base of the channel is a thin (< 1m) drape of sediment (sf_{10}) that is succeeded by mutli-story stacking of sf_6 (Table 6.1 and Fig. 6.6c). A vibrocore survey by Wessex Archaeology (2008) uncovered the lithology of deposits associated with each seismic facies, which is summarised in Table 6.3 and Figure 6.6c. When tied to seismic facies, the sedimentary facies demonstrate a transition from coarse grained gravel (Gm) at the base of the channel to laminated sands (Sfp) within the channel with increasingly shell rich sands towards the surface (Sh and Smw) (Table 6.2 and Fig. 6.6c). The association of seismic facies and sedimentary facies are interpreted to represent deposition of a coarse-grained basal lag subsequent to channel incision followed by deposition of estuarine and shallow marine sediments in response to sea-level transgression (Fig. 6.6c).

6.4.3 Stratigraphy and chronology

Erosion surfaces are cut into bedrock and overlain by shallow marine, coastal and fluvial deposits. OSL and ^{14}C ages in the range of 176.6 ± 20 ka to 5.3 ± 0.5 ka (Table 6.3) provide a chronological constraint to deposition on the continental shelf over at least two glacial-interglacial cycles (Wessex Archaeology, 2008; Mellett et al., 2012b). OSL and ^{14}C ages obtained by Wessex Archaeology (2008) are inconsistent within the same core, at the same depth, with a ^{14}C age (9160-8350 cal. BC) underestimating an OSL age (14.2 ± 1.1 ka) by approximately 3 ka (~20%).

According to the chronometric data, sediments within the channel belt overlying surface T3 were deposited during marine oxygen isotope stage MIS 6 and the late stages of MIS 5 (Fig 6.12). Exposure of surface T4 and deposition of sediments associated with surface ME occurred during MIS 2. This places formation of surface T4 at some point between the late sub-stages of MIS 5 and MIS 2. Partial infilling of surface ME and deposition of coastal sediments on surface T1 correlate to MIS 1 (Mellett et al., 2012b).

6.4.4 Formation of erosion surfaces

The similar morphologies of surfaces T1 and T2 (see section 6.4.1) may suggest that they were formed by similar processes. Widespread erosion and formation of seaward-dipping planar surfaces can occur during sea-level transgression (Bradley and Griggs, 1976). Initial formation of surface T1 has been linked to marine planation during Neogene transgressions when the English Channel basin first became a marine embayment (Lautridou et al., 1986; Curry, 1989; Gibbard et al., 1988; Stride, 1990; Hamblin et al., 1992). The stepped margin separating surface T1 from all other surfaces has been interpreted as a submerged cliff line that formed during Neogene sea-level stillstands (Kellaway et al., 1975; Hamblin et al., 1992). The data presented here support such a model.

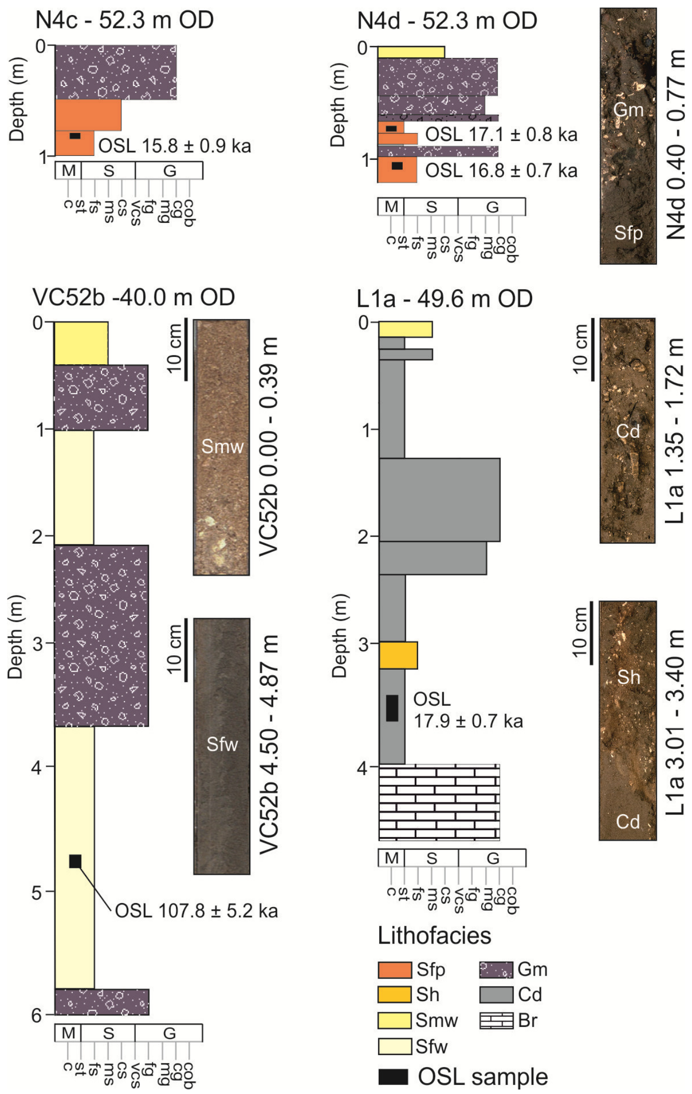


Figure 6.11: Sedimentary logs and core photographs showing stratigraphy and lithological composition of sedimentary facies discussed in Table 6.2. Locations of vibrocores are highlighted in Figure 6.2 and correlated to seismic lines in Figures 6.4 and 6.5. The location of OSL samples and resulting ages (Mellett et al., 2012b) are given.

Using formation of T1 as a basis, surface T2 can also be considered the product marine planation, but during a later phase of marine transgression. Erosion of this surface would have occurred prior to opening of the Straits of Dover, dated to MIS 12 (Toucanne et al., 2009a). Surface T2 is drained by a dendritic channel network. Given the limited size of these channels it is unlikely that they acted as a conduit for drainage during breaching of Straits of Dover and probably reflect more localised incision in response to regression. Sediments currently preserved on surfaces T1 and T2 originate from palaeovalley infill and shoreline retreat during the Holocene transgression. Therefore, a significant hiatus between erosion and deposition is apparent.

Seismic profiles indicate that surface T3 formed through fluvial erosion of individual channels within a channel belt complex that combined to create a bedrock strath surface. Individual channels show evidence of lateral and downstream mobility that together with transport of a coarse-grained bedload, represented by a basal lag, is responsible for incision and valley widening during cold stages (Lewin and Gibbard, 2010). A single OSL age of 176.6 ± 20 ka (Table 6.3) from fluvial deposits overlying surface T3 suggests that, at least locally, incision occurred during or prior to the early parts of MIS 6. However, individual palaeovalleys are infilled with transgressive deposits dating to the early sub-stages of MIS 5, which have subsequently been partially eroded and reworked by renewed phases of fluvial incision. Therefore, erosion of surface T3 cannot be linked to a single climatic event. Whilst surface T3 demonstrates characteristics of a strath surface, the variable lithological composition of sediments within the channel belt complex and the degree of variability recorded in seismic profiles suggests that composite erosion was achieved through repeated phases of incision in response to fluctuating sea levels, rather than channel avulsion across a broad fluvial plain.

Sediments preserved on surface T4 show that subsequent to incision the area was sub-aerially exposed and subjected to periglacial conditions during MIS 2. A hiatus between incision and deposition is inferred as localised weathering of bedrock alone cannot explain the formation of surface T4. Subsequent modification by surface ME precludes confident interpretation of the erosion mechanisms. Surface T4 may have encompassed the area now occupied by the Northern Palaeovalley, as remnants of this surface are preserved at the valley margins. Incision of parallel-aligned, linear grooves (low sinuosity channels Fig. 6.9) show a morphological resemblance to bedrock furrows described in Richardson and Carling (2005). These features are typically attributed to fluvial erosion but they can also occur in tidal environments where bedrock is sufficiently erodible (Carling et al., 2009). In the eastern English Channel, these furrows are confined to the relatively softer bedrock of the Hampshire-Dieppe basin suggesting underlying lithology has some control over their formation. Based on the available data, distinguishing between fluvial or tidal erosion is not possible. Elsewhere, surface T4 forms the base of a broad palaeovalley that is confluent with the Median Palaeovalley in central English Channel (Fig. 6.1) and indicates that at least part of surface T4 formed through fluvial incision. Erosion of this surface occurred at some time during MIS 4-3 when the continental shelf was sub-aerially exposed (Fig. 6.12).

Planform and cross-sectional geometries of surface ME in the SB Palaeovalley suggest incision was driven by vertical downcutting of a bedrock confined fluvial channel. Assuming deposition of a basal lag on top of surface ME is a product of the processes driving erosion, an OSL age from this deposit provides a chronometric constraint for incision at ca. 21 ka (Table 6.3).

A change in morphology between the SB Palaeovalley and the Northern Palaeovalley indicates a change in erosive regime. Bedrock morphology of the Northern Palaeovalley has been interpreted as the product of high magnitude flow regimes linked to catastrophic flooding through the Straits of Dover (Smith, 1985; Gupta et al., 2007). At least in part this morphology is constructional resulting from deposition of sediments from a laterally migrating point bar along the margin of the Northern Palaeovalley. Fluvial regimes operated between 15.8 ka and 17 ka according to the deposits preserved. Here, formation of the erosion surface is driven by fluvial processes as seismic reflectors are concordant with the underlying erosion surface.

The time relationship between the formation of mid-channel bedrock bars and deposition of laterally migrating point bars in the Northern Palaeovalley is unknown. The mid-channel bedrock bars may be a remnant of antecedent fluvial regimes or of megaflood processes (Gupta et al., 2007) prior to occupation of the Northern Palaeovalley by a mobile channel during MIS 2. Alternatively, erosion of the mid-channel bars may have occurred at the same time as deposition at the valley margins. Large glacial meltwater-fed, cold-climate gravel-bed rivers can exhibit a full range of fluvial styles within the same channel reach (Vandenberghe, 2001) and alluvial point bars and bedrock mid-channel bars can be created simultaneously, especially in areas where bedrock is exposed and susceptible to periglacial weathering.

Erosion Surface	Location	Depositional Environment	Core	Depth (m OD)	Dating Method	Age	Reference
T1	Hastings Bank	Coastal (washover fan)	VC37a	-16.81	OSL	5.3 ± 0.5	Chapter 4 Chapter 5
		Shallow marine	VC28	-19.11	OSL	7.8 ± 0.2	
		Shallow marine	VCL3b	-13.7	OSL	8.4 ± 0.2	
		Coastal (nearshore beach)	VC37b	-24.02	OSL	8.0 ± 0.6	
T3	Channel belt complex	Shallow marine	VC52b	-48.8	OSL	107.8 ± 5.2 ka	Chapter 5
	SB Palaeovalley (alluvial terrace)	Marine marginal	VC7	-41.56	OSL	83.2 ± 6.6 ka	Wessex Archaeology (2008)
		Fluvial (palaeosol)		-42.88	OSL	176.6 ± 20 ka	
T4	Northern Palaeovalley margin	Periglacial (head deposit)	VCL1a	-53.1	OSL	17.9 ± 0.7 ka	Chapter 5
ME	Northern Palaeovalley	Fluvial (point bar)	N4c	-53.2	OSL	15.8 ± 0.9 ka	Chapter 5
		Fluvial (point bar)	N4d	-53.4	OSL	16.8 ± 0.7 ka	
		Fluvial (point bar)	N4d	-52.7	OSL	17.1 ± 0.8 ka	
	SB Palaeovalley	Shallow marine	VC1	-47.90	C^{14} (shell)	7320-6860 cal. BC	Wessex Archaeology (2008)
		Marine marginal	VC1	-48.03	OSL	11.9±0.9 ka	
			VC1	-48.86	C^{14} (shell)	9160-8150 cal. BC	
		Marine marginal (estuarine to freshwater)	VC3	-55.12	OSL	14.2 ± 1.1 ka	
			VC3	-55.13	C^{14} (shell)	9160-8350 cal. BC	
		Alluvial or tidally influenced	VC3	-55.58	OSL	15.1 ± 1.2 ka	
		Fluvial (basal lag)	VC5	-49.34	OSL	21.2 ± 1.5 ka	

Table 6.3: Age data. Locations of cores, with the exception of those recoverd by Wessex Archaeology (2008), are shown in Fig. 6.3. Refer to citations for full methodological details.

Secondary drainage networks of considerably smaller magnitude are located on the bedrock bar surfaces within the Northern Palaeovalley (Gupta et al., 2007), which have been interpreted as representing periods of 'normal fluvial processes'. According to the data presented here, the secondary drainage networks identified by Gupta et al., (2007) are considerably undersized in comparison. These secondary drainage networks show a similar morphology to cross-bar channels commonly observed in gravel-bed braided rivers (Bridge and Lunt, 2006). Therefore an alternative hypothesis may suggest these superimposed minor drainage networks are the result of cross-bar bedrock scour during periods of high flow.

Separation of seismic facies by an erosional surface within sediments preserved at the margin of the Northern Palaeovalley marks a change in sedimentary regime after ca. 16 ka that is probably related to reworking by tides during Holocene sea-level rise. This shows the erosive power of tides propagating through and confined within the Northern Palaeovalley, as they can produce erosional bedforms characteristic of high magnitude flows-particularly in less resistant lithologies (Carling et al., 2009). Whilst it is not possible to fully resolve the nature of processes responsible for formation of the Northern Palaeovalley, it is apparent that incision is at least partly controlled by fluvial processes operating during MIS 2 and erosion by coastal and shallow marine processes during Holocene transgression.

A summary of the sedimentary processes driving evolution of the continental shelf evolution from MIS 6 to MIS 1, as interpreted from erosional and depositional evidence preserved in the eastern English Channel, is presented in Figure 6.12.

6.5 DISCUSSION

Seismic stratigraphic, sedimentological and chronometric data from the eastern English Channel reveal that sculpting of the continental shelf occurred during multiple erosional phases resulting in the formation of a major composite erosion surface. Preservation of sediment on this bedrock erosion surface is typically confined to palaeovalleys or relict coastal landscapes. The data presented in this paper provide a framework to reconstruct the Mid- to Late Pleistocene palaeogeographic configuration in the eastern English Channel (Fig. 6.13). Reconstructions are subdivided into time periods that correlate to the marine isotope record and Northwest European chronostratigraphic stages (Gibbard and Cohen, 2011). With the exception of the Holocene (MIS 1), interglacial periods are not discussed as no sedimentary records corresponding to these time periods were encountered in the

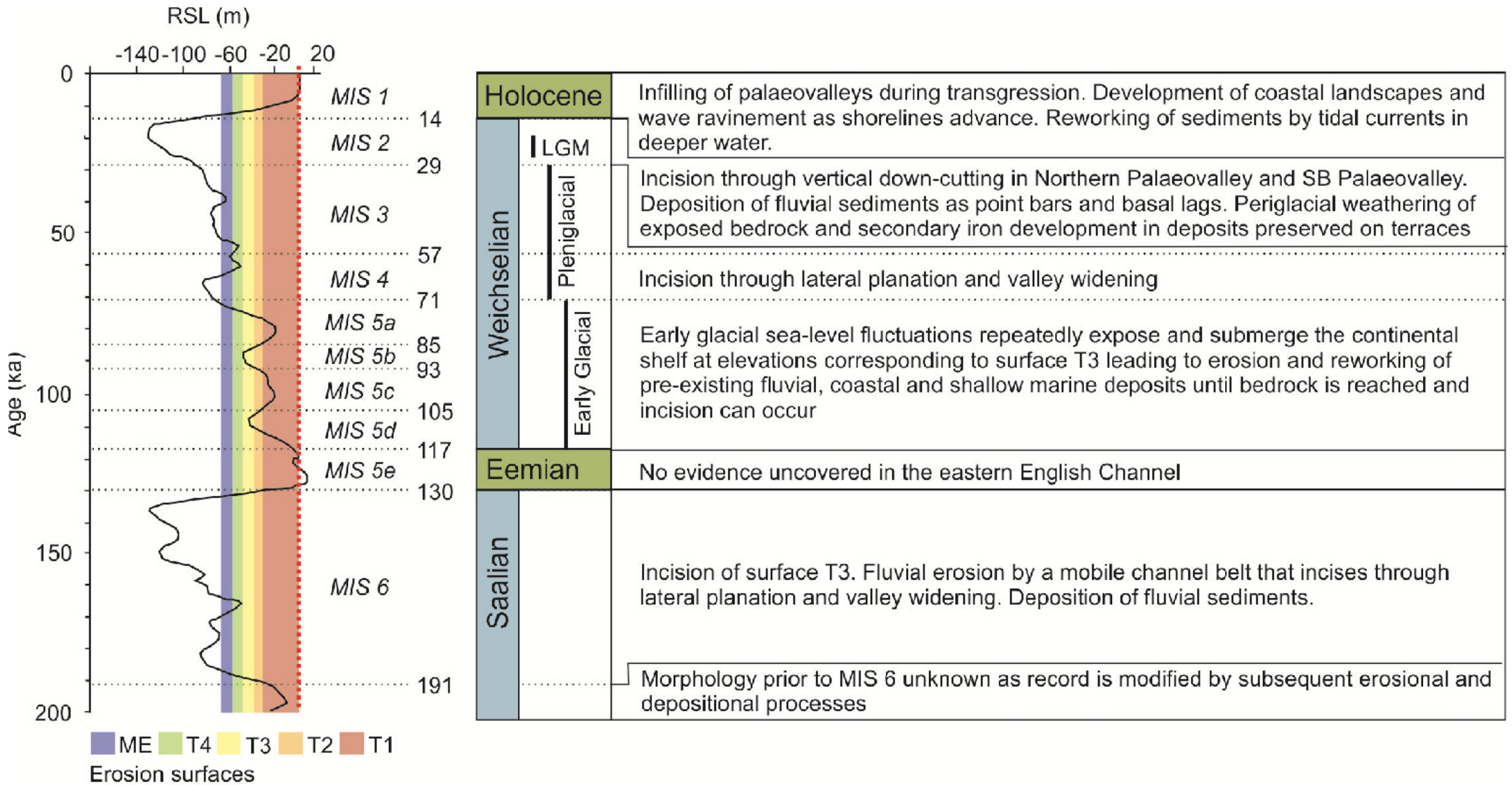


Figure 6.12. Erosional and depositional records preserved on the eastern English Channel continental shelf presented alongside the marine isotope record (Lisiecki and Raymo, 2005) and a global sea-level curve (Waelbroeck et al., 2002) during the mid- to late Quaternary. Chronostratigraphic subdivision is based on Gibbard and Cohen (2011). Timing of the Late Glacial Maximum (LGM) after Clark et al. (2009). Elevations of erosion surfaces shown on the relative sea-level curve with present day sea-level highlighted by a red dashed line. Interpretations of sedimentary regimes during each stage are based on the data presented in section 6.4.

eastern English Channel. This may have been due to the distribution of cores, where a bias towards coarser grained sediments was incorporated into the selection of sites. However, on the continental shelf, interglacials are periods of relative sedimentary quiescence when compared to glacial stages, thus having less persistence in the sedimentary record. Further, there is a greater chance of reworking as successive erosion phases modify the morphological and sedimentary evidence of previous periods and as a consequence, only the most recent phase of erosion and deposition is preserved. The degree to which climate, relative sea level, sediment supply and discharge have influenced the timing and nature of shelf erosion and deposition is addressed by linking the submerged palaeovalleys of the eastern English Channel with pre-existing fluvial archives and sedimentary records at the shelf margin. Here we illustrate that knowledge of the timing and duration of processes operating at the basin-wide scale, and the persistence of landscapes thus created (cf. Brunsden, 1993), is essential to understand continental shelf evolution and distinguish between 'normal' and 'catastrophic' processes.

6.5.1 Palaeogeography and drainage configuration in the eastern English Channel

Saalian Drenthe (MIS 6)

Locally, fluvial incision of surface T3 corresponds to a period of climatic deterioration associated with the extensive Saalian (Drenthe substage) glaciation in Northwest Europe during MIS 6 (Graham et al., 2011). A significant base level fall of 120 m (Waelbroeck et al., 2002) would have steepened the fluvial profile and led to incision. Coalescence of the British and Fennoscandian ice sheets in the central North Sea basin forced the Thames and Scheldt fluvial systems southwards towards the Straits of Dover (Bridgland et al., 1993; Bridgland and D'Olier, 1995; Gibbard, 1995; Bridgland and Gibbard, 1997). Incision at the Straits of Dover produced a lowered base level which is reflected by widespread erosion in the Netherlands and southern North Sea (Busschers et al., 2008; Hijma and Cohen, 2011). This incision may have been driven or reinforced by potential 'catastrophic' discharge from a proglacial lake in the southern North Sea (Murton and Murton, 2012). However, the imprint such discharges leave on the landscape is difficult to determine and may be buffered by 'normal' background levels that are influenced by the dynamics of major NW European ice sheets and a very large catchment size. It is expected that effective drainage capture by the eastern English Channel of the Thames and Rhine-Meuse fluvial systems through the Straits of Dover would have increased sediment and water discharge above the capacity of existing rivers (Somme, Canche and Authie) and encouraged incision through the creation of new channel networks. Sediment supply would have been maintained by erosion of Mesozoic and Cenozoic strata, particularly Cretaceous chalk at the Straits of Dover, producing an abundant supply of flint for bedload transport within the palaeovalley network. During this time the fluvial regime would have been moderated by weathering and weakening of the underlying bedrock (Murton and Lautridou, 2003) and sediment flux derived from hillslopes (Murton and Belshaw, 2011), both conditioned by periglacial processes.

Seismic and bathymetric data show that the resulting palaeovalley network adopted a general E-W drainage configuration confluent with the Median Palaeovalley and Palaeo-Seine in the central English Channel (Lericolais et al., 2003) (Fig. 6.13a). The morphology preceding this erosion phase is unknown because parts of surface T3 form the oldest fluvial terrace preserved in the eastern English Channel. Incision may have extended northwards to the area that is now the Northern Palaeovalley and was potentially constrained by the morphology of surfaces T1 and T2. However, subsequent erosion of the record makes it difficult to confirm this. It is apparent that flow was confined to a single channel (Lobourg Channel, Fig. 6.1) in the relative uplands of the Weald-Artois anticline and became more distributive within the Hampshire-Dieppe basin. This drainage configuration may simply have been the product of antecedent morphology. However, there is potential for vertical incision and formation of the Lobourg Channel to have been partially driven by uplift and tilting of the Weald Artois anticline in response to glacio-isostatic uplift in front of ice sheet margins (Busschers et al., 2008).

A single OSL age is available to constrain the incision to a period of increased 'Channel River' activity where peak discharges occurred at ca. 155 ka (Toucanne et al., 2009b). During this time discharge was primarily attributed to meltwater flux during ice sheet retreat between the Drenthe and Warthe advances of the Saalian glacial (Toucanne et al., 2009b), although Meinsen et al. (2011) suggested that catastrophic discharge from proglacial lakes in Northwest Europe may have flowed through the English Channel during this time.

Early Weichselian glacial (MIS 5a-5d)

Relative sea-level fall during the transition from the Eemian (MIS 5e) to early Weichselian was not linear and globally sea-level fluctuated between a minimum of -30 m OD and a maximum of -80 m OD during MIS 5a-5d (Waelbroeck et al., 2002). This meant that for a long period (at least 55 ka) the eastern English Channel was a marine marginal environment where the interactions between fluvial and marine processes were controlled by several sea-level oscillations (Fig. 6.12). Fluvial systems during the initial sea-level fall of MIS 5d extended offshore onto the continental shelf. Most likely they reoccupied and modified valley networks formed during previous lowstands, and in many places, eroded sediments preserved within the palaeovalleys. As base-level continued to fall, incision of the underlying bedrock (surface T3) was initiated. During this time the palaeovalleys were most likely a conduit for sediment throughput and deposition appears to have been restricted to basal lags. Locally, lateral and downstream channel migration has helped to preserve some sediments associated with earlier phases of deposition.

Minor transgressions punctuate the overall falling trajectory of sea level during the early glacial. At elevations where these transgressions flood palaeovalleys, there is the potential for deposition of coastal and shallow marine sediments as accommodation is created and shorelines step landward. Sediment supply may have been maintained through reworking of pre-existing deposits in a coastal plain setting as the interface between fluvial and marine processes shifted in response to changes in sea level (Fig. 6.13b). Phases of sediment reworking, incision and deposition as discussed above are expected to have operated over each stadial to inter-stadial sea-level cycle resulting in formation of a composite sheet of sediment and partial erosion of surface T3. There are no other deposits of the extent and thickness of the early Weichselian deposits preserved in the eastern English Channel. This reflects the uniqueness of the sea-level and climate history at these elevations during this period.

Weichselian Pleniglacial (MIS 4-3)

Initial climatic deterioration and associated sea-level fall during Late MIS 4 and MIS 3 led to sub-aerial exposure of the continental shelf in the eastern English Channel. Sediments deposited on surface T3 during MIS 6 to early sub-stages of MIS 5 were spared from significant physical reworking but subjected to chemical weathering, evident from the development of secondary iron, particularly in coarser grained sediments. During this time, ice sheets were expanding from Northern Scotland and Scandinavia (Ehlers and Gibbard, 2004) and the Thames and Rhine-Meuse fluvial systems occupied antecedent channel networks and flowed south through the Straits of Dover into the eastern English Channel (Bridgland et al., 1993; Bridgland and D'Olier, 1995; Busschers et al., 2007). Sediment flux, as a proxy for discharge, through the 'Channel River' to the continental shelf margin was significantly less than during MIS 6 or MIS 2 (Toucanne et al., 2009b). Despite this, the eastern English Channel records an episode of substantial fluvial incision, suggesting discharge was high enough to enable erosion.

Extension of the Lobourg Channel into the eastern English Channel partially eroded sediments associated with earlier phases of palaeogeographic development (MIS 6 – MIS 5) (Fig. 6.13c). Incision in the area of the Northern Palaeovalley occurred, potentially taking advantage of existing drainage configurations forged during previous sea-level lowstands. Valleys appear to have adopted a general E-W to NE-SW trend extending westwards to the continental shelf margin (Fig. 6.13c). The exact timing and nature of processes driving incision is unknown. Upstream, the Rhine-Muese system records a phase of extensive reworking and lateral erosion during MIS 4 followed by a phase of aggradation during MIS 3 (Busschers et al., 2007). However, linking the timing of incision in the English Channel to the behaviour of the Rhine-Muese system is problematic due to different time delays in the response to external controls along the catchment profile.

Weichselian – Last Glacial Maximum (MIS 2)

Chronometric data for the SB Palaeovalley and Northern Palaeovalley places bedrock incision by fluvial processes in the period of maximum sea-level lowstand (-120 m OD) at the Last Glacial Maximum (LGM) between 26.5 ka and 19 ka (Clark et al., 2009). During this time drainage beyond the Straits of Dover appears to have adopted a westerly direction following a structural fold (SB Palaeovalley) after emerging from the Lobourg Channel (Fig. 6.13d). The morphology of erosion surface ME suggests dominant flow then returned to a SW direction within the Northern Palaeovalley to become confluent with the Median Palaeovalley and Palaeo-Seine within the central English Channel (Fig. 6.1).

Given the relative timing during a sea-level lowstand period, the deep fluvial incision is interpreted to have been driven by steepening of the fluvial profile to a base-level that was maintained for a period of time sufficient to enable knick point retreat to extend 500 km upstream. Assuming that the knick point started at a lowstand shoreline where a noticeable change in the shelf gradient was exposed (0.00008 to 0.0002 at -70 m OD), the rate of knick point retreat during the last glacial would be ca. 20 km/ka according to the duration of time sea level was below this break in slope (Siddall et al., 2003), and the distance between the retreating shoreline and the knick point. The timing of incision and corresponding deposition within the Northern Palaeovalley correlates to a period of enhanced discharge through the English Channel that appears to be coupled to the collapse of the British and Fennoscandian ice sheets between 20 ka and 17 ka (e.g. Toucanne et al., 2010). Whilst it is expected that incision would principally be driven by relative sea-level fall, the depth of incision may have been enhanced or modified by sediment-laden waters at the onset of ice sheet collapse, the routing pattern guided by lithological changes and

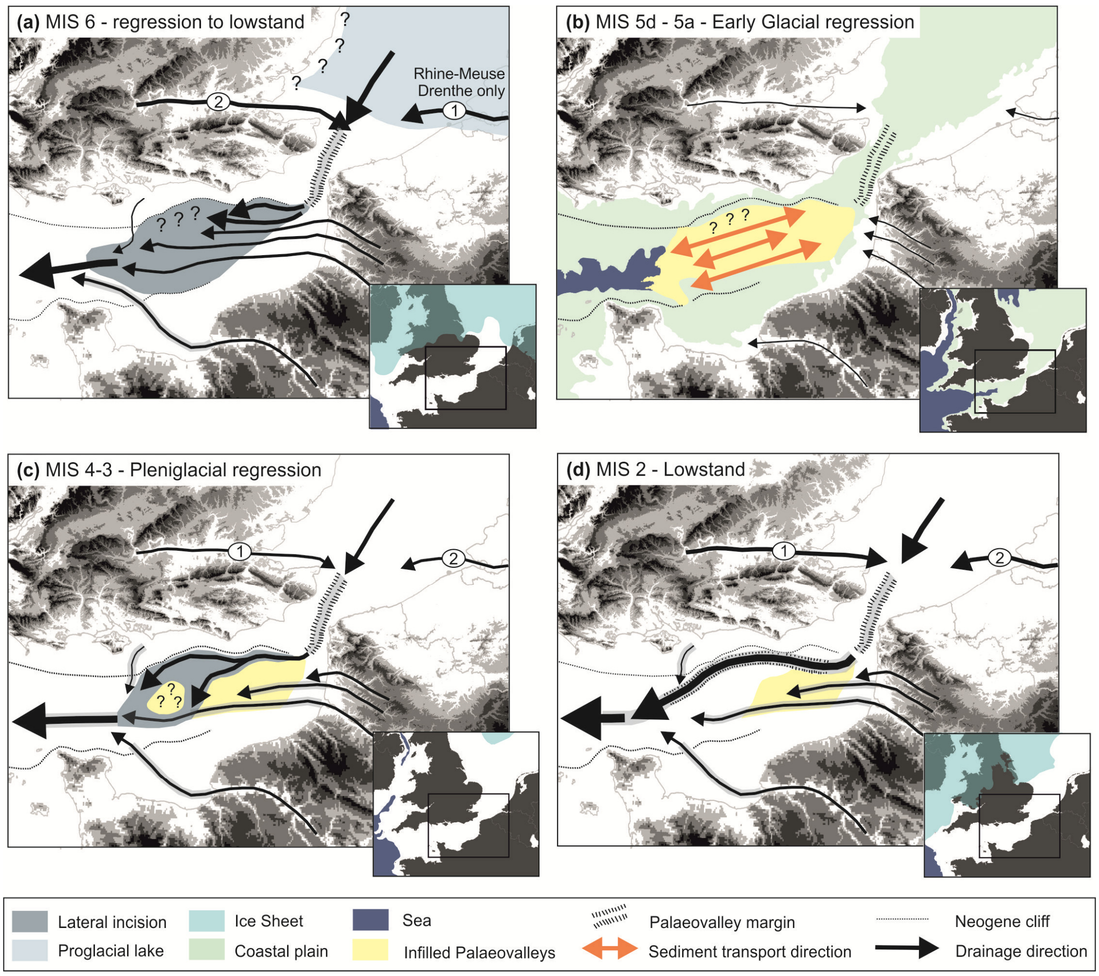


Figure 6.13: Palaeogeography and drainage configurations in the eastern English Channel during; (a) MIS 6; (b) MIS 5d-5a; (c) MIS 4-3, and: (d) MIS 2. Black arrows show the direction of drainage and the thickness is proportional to discharge with thicker lines indicating higher discharges. The extent of the MIS 6 proglacial lake is based on Busschers et al. (2008) and, Murton and Murton (2012). The position of the Rhine-Meuse (1) is taken from Busschers et al. (2008) and the position of the Thames (2) from Bridgland and D'Olier (1995). Ice margins are taken from Ehlers and Gibbard (2004). Shoreline locations are based on global relative sea-level history (Waelbroeck et al., 2002) and the bathymetry of the continental shelf.

tectonic structures in the bedrock geology, and the rate of knick point retreat according to shelf topography. In addition significant weakening of exposed bedrock at this time (surface T4) produced a basement susceptible to erosion.

Age data place deposition within the Northern Palaeovalley between ca. 17 ka and 16 ka. In the Rhine-Meuse system, this time period is characterised by downstream sediment transport and reworking of older deposits (Busschers et al., 2007). Mineralogical analyses of sediments preserved within the Northern Palaeovalley indicate a partial Rhine origin (Busschers, pers. comm.). This would suggest that sediment routing from source to sink is not one of continuous throughput and bypass. The data presented here reveal that palaeovalleys on the continental shelf in the eastern English Channel act as temporary or minor sediment sinks. However, a more highly resolved chronology is required to understand response and lag times along the catchment profile.

Holocene (MIS 1)

In the eastern English Channel part of the palaeovalley network created during MIS 2 is infilled with deposits typically associated with a transgressive system tract (Miall, 2006). The sedimentary succession is comparable to palaeovalley fills preserved elsewhere in the English Channel during the Holocene sea-level transgression (Bellamy, 1995; Velegrakis et al., 1999; Gupta et al., 2004; Tessier et al., 2010). Deposition during relative sea-level rise is principally driven by the interaction between the creation of accommodation and sediment supply (Posamentier and Allen, 1999).

The SB Palaeovalley becomes confluent with the Northern Palaeovalley in the eastern English Channel. Whilst the SB Palaeovalley is completely filled, the Northern Palaeovalley is underfilled. This could be attributed to differences in valley morphology, where greater accommodation is created Northern Palaeovalley in comparison to the SB Palaeovalley, due to a larger cross-sectional area. Under these conditions an additional sediment source would be required to ensure complete filling the Northern Palaeovalley. However, the degree to which the Northern Palaeovalley was initially filled during early transgression is difficult to constrain, as due to the valley morphology there is significant potential for coastal and shallow marine processes during Holocene sea-level rise to rework any pre-existing valley infill. A bedload segregation zone in the Northern Palaeovalley around a tidal amphidromic point in the vicinity of the Isle of Wight triggered the transport of sediment towards the Straits of Dover (Anthony, 2002; Uehara et al., 2006) and may have promoted excavation of the (partially filled) Northern Palaeovalley. The ability for tidal processes to entrain and erode would strongly depend on the seabed morphology and grainsize of the palaeovalley fill. In addition, changes in the tidal regime in relation to reconnection of the North Atlantic with North Sea waters through the Straits of Dover at 8 ka (Scourse and Austin, 1995; Shennan et al., 2000) would complicate the matter further.

Deposits associated with sea-level transgression are not limited to palaeovalley fills (Mellett et al., 2012a). Coastal environments migrate landward in response with rising sea levels and, under certain circumstances, can be preserved. Reworking of finer sandy sediments into bedforms (sediment waves) and modification of seabed morphology by tidal currents during the later stages of the Holocene is expected (Anthony, 2002; Cazenave, 2007).

6.5.2 Catastrophic flooding in the English Channel

It has been proposed that one or more catastrophic flood events where responsible for producing the erosive morphology of the Northern Palaeovalley in the English Channel (Smith 1985; Gupta et al., 2007). However, the mechanism for generating a megaflood through erosion of a bedrock ridge is poorly defined. The timing of the proposed flood, or indeed floods, has been linked to glacial-maxima during MIS 12 (Toucanne et al., 2009a) and/or MIS 6 (Meijer and Preece, 1995), and largely depends on the existence of a proglacial lake in the southern North Sea basin (Gibbard et al., 1988). The depositional record in the eastern English Channel is biased towards the most recent glacial-interglacial cycle and the sediments preserved are associated with relict coastlines and palaeovalley fills. No evidence was uncovered of constructional bedforms typically associated with catastrophic floods (e.g. Carling et al., 2009). In addition, the data presented here demonstrates that continental shelves are highly susceptible to reworking at the glacial-interglacial timescale. Therefore, if flood events did occur during MIS 12 and/or MIS 6, the sedimentary record of these events is likely to have been destroyed.

The erosional record in the eastern English Channel is composite and the morphology prior to MIS 6, particularly in the Northern Palaeovalley, cannot be constrained. There is evidence to suggest that 'normal' fluvial processes were at least partly responsible for shaping the Northern Palaeovalley during MIS 2, thus contradicting the conclusion by Gupta et al. (2007) that the morphology is the product of two discrete flood events. There is a possibility that the Northern Palaeovalley was sculpted by 'catastrophic' floods and then later reoccupied by a fluvial system. However, to preserve the antecendent flood morphology would require the fluvial regime operating during subsequent sea-level lowstands to have limited erosive capabilities, which contradicts present models of fluvial behaviour in response to climate and sea-level change (Blum and Törnqvist. 2000; Vandenberghe, 2008; Gibbard and Lewin, 2009). Assuming a megaflood event akin to a glacial outburst flood (e.g. Bretz, 1969) was not responsible for erosion of the bedrock ridge at the Straits of Dover, alternative hypotheses proposed are; (i) gradualistic erosion through fluvial downcutting by discharge from the Thames and Rhine rivers systems, or; (ii) episodic erosion driven by high frequency, high magnitude discharges conditioned by fluctuating ice margins and the presence or absence of proglacial lakes in the southern North Sea. A combination of both may be responsible for the morphology preserved and a more highly resolved chronological framework is required to test this. It is suggested here that multiphase processes operating over a long period of time (at least 200 ka) sculpted the eastern English Channel continental shelf, creating a landscape that has a similar morphological character to one produced instantaneously by a catastrophic event.

6.6 CONCLUSIONS

The landscape preserved on the present-day seabed of the eastern English Channel is a record of the sedimentary processes operating over glacial-interglacial sea-level cycles from MIS 6 to MIS 1. The mid- to late Quaternary landscape is a palimpsest of composite erosion surfaces formed through multiple phases of fluvial incision and a fragmentary and highly reworked depositional record that is biased towards sedimentary processes operating in shallow marine and coastal environments. The extensive volumes of coarse clastic sediments that are uncharacteristic for the erosional landscape of the English Channel continental shelf, and an essential aggregate resource, formed over multiple sea-level cycles as a multi-lateral, multi-storey succession of palaeovalley fills.

Fluvial incision occurs during relative sea-level fall or lowstand and correlates to periods of cold climatic conditions where bedrock is weakened by periglacial weathering. In part, fluvial incision may be coupled to ice sheet dynamics and ice front palaeogeography, with increased discharges during phases of retreat. Palaeovalleys then infill as accommodation is created during sea-level transgression and sediment is supplied initially through bedrock erosion, but maintained through continuous recycling of terrestrial deposits over glacial-interglacial sea-level cycles. Evidence of sea-level highstands in the form of deposits during interglacial periods appears not to be preserved on the continental shelf. Further, the stratigraphic record is incomplete and sediments, as well as erosion surfaces, associated with each sea-level stage are only partially preserved. As in most environments, the shelf record is biased towards the present-day. Over successive relative sea-level cycles the morphological and sedimentological expressions of sedimentary processes become superimposed upon each other and environmental information from the most recent glacial to inter-glacial cycle is preferentially preserved.

In the eastern English Channel there are no unequivocal erosional or sedimentological records of the processes operating during MIS 12 preserved. Understanding palaeogeographic development during this time, particularly in relation to the mechanisms driving breaching of the Weald-Artois anticline at the Straits of Dover, is problematic due to later bedrock erosion and multi-phase recycling of sediments. Evidence is preserved to support major erosion during MIS 6. However, sedimentary processes during this time alone cannot account for the morphology of the Northern Palaeovalley as it was at least partly re-sculpted by fluvial processes during MIS 2. Events of catastrophic magnitude are not necessarily responsible for formation of the palaeovalley network preserved in the eastern English Channel and it is much more likely that the landforms were created by processes of non-catastrophic magnitude operating over long (10^4 yrs) periods of time.

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Chapter 7

Discussion and conclusions

This thesis set out to address a series of research questions as outlined in Chapter 1. The data presented in Chapters 4 to 6 do not explicitly address these questions. Therefore, the objective of this chapter is to provide a summary of the main findings and discuss these in relation to those initial questions posed. Further, the wider implications of this research and recommendations for future work will be discussed.

7.1 DROWNED LANDSCAPES OF THE EASTERN ENGLISH CHANNEL

Question 1: *What landscapes and sediments are preserved on the eastern English Channel continental shelf and what are the principal controls on landscape development?*

The continental shelf in the eastern English Channel preserves a rich but complicated variety of ancient landscapes that formed during periods of lowered sea-level. These include early Holocene relict coastal landscapes (see Chapter 4), periglacial head deposits, and paraglacial fluvial systems that have evolved through time to create an erosional landscape (see Chapter 6).

A large proportion of the sediments preserved in the eastern English Channel were deposited in a coastal to shallow marine setting. Sediments are both constructional, whereby they form a range of coastal/shallow marine landforms that include barrier shorelines, washover fans, back barrier inlets and tidal bedforms, and composite, whereby they infill valleys created by fluvial processes. The influence of the marine environment on depositional processes is represented by an abundance of marine fauna, including mollusca and foraminifera, within sediments. The expression of fluvial systems dominates the erosional landscape and a complicated network of palaeovalleys has been preserved. Preservation of fluvial deposits is rare but can occur at the base and margins of palaeovalleys. Sediment preserved on the shelf typically comprise sand and gravel that has been recycled within the continental shelf environment by marine, coastal and fluvial processes over repeated sea-level cycles. Finer grained sediments are restricted to back-barrier settings, estuarine channels and weathered bedrock surfaces.

The timing and nature of processes responsible for the development of landscapes on the eastern English Channel continental shelf are presented in chapters 4 and 6. In an environment that experiences such dramatic fluctuations in sea-level, erosion and deposition is principally driven by changes in base level. However, the data presented in this thesis demonstrate that it is possible to resolve higher frequency controls on landscape development by chronometrically constraining the erosional and depositional record.

In the eastern English Channel, phases of valley incision occur during periods of increased discharge correlating to the time of ice sheet collapse (Toucanne et al., 2009b; 2010). Further, the drainage configuration of fluvial systems in NW Europe (Chapter 6), conditioned by the location of ice, and presence or absence of a land bridge at the Straits of Dover, influences how much water travels through the continental shelf environment and determines the nature of fluvial response i.e. incision or deposition. Locally, the depth and path of fluvial incision is governed by changes in rock type across faults and folds in the bedrock. Only with an understanding of the subsurface geology obtained through analysis of seismic profiles was this relationship established.

During relative sea-level fall or lowstand, the continental shelf becomes a region of sediment throughput with minor phases of storage within the fluvial environment. During relative sea-level rise, fluvial valleys are filled with sediment deposited in shallow marine, estuarine or coastal settings. This is principally driven by the balance between accommodation and sediment supply under rising sea-levels but can also be influenced by antecedent topography and tidal regime (Chapter 6). Drowning of valleys during sea-level highstand, as long as they are beyond the influence of waves and tides, is a mechanism for temporary storage of sediment on the continental shelf and retaining a supply for lowstand systems during subsequent sea-level fall.

The stratigraphy preserved at Hastings Bank (Chapter 4), established through the integration of a variety of high resolution data sources, provides the opportunity to assess the shoreline process-response to relative sea-level rise at a point in time and space. An assessment of age was made by linking the elevation of landforms to a relative sea-level curve for the southeast coast of Britain (Fig. 7.1) that places development of the barrier complex during the early Holocene. This age estimate was confirmed through OSL dating of sediment recovered from Hastings Bank (Chapter 5), which revealed ages in the range of 8.4 ± 0.2 ka to 5.3 ± 0.5 ka. The chronometric data can be used to further constrain relative sea-level history, which acts as a benchmark to assess landscape change as a function of the relationship between accommodation and sediment supply.

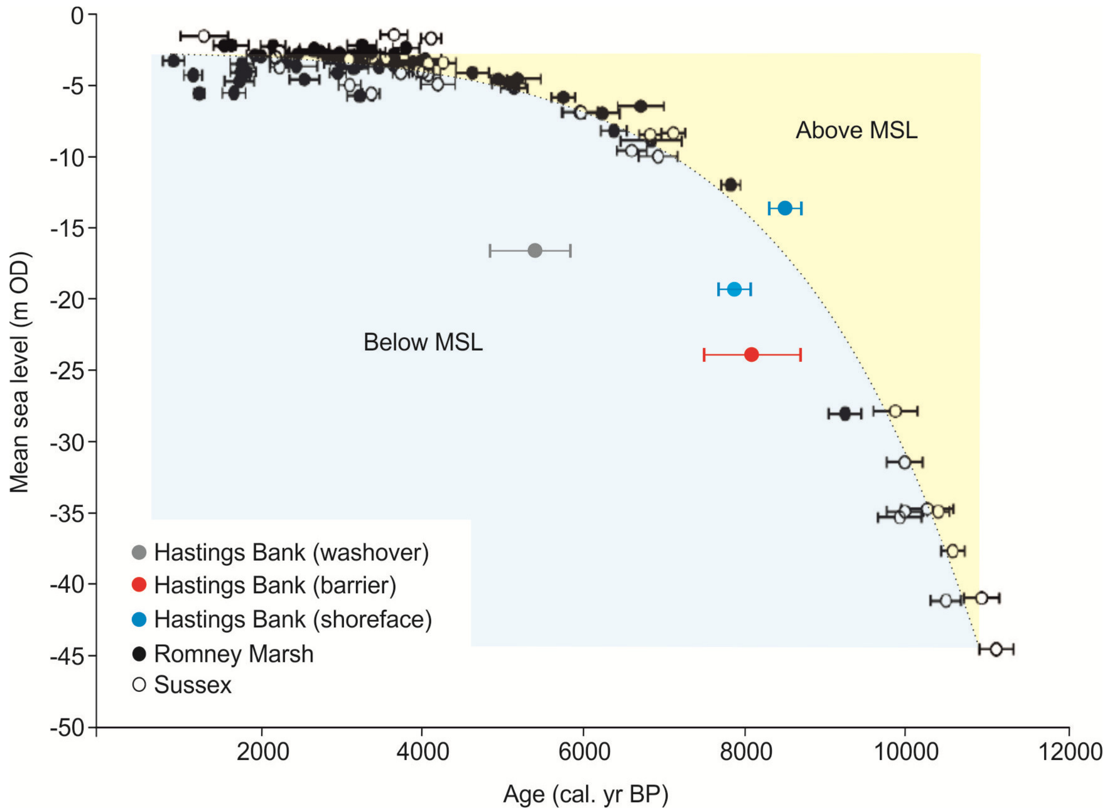

Figure 7.1: Plot of sea-level index points for south-east Britain reproduced after Waller and Long (2010) including OSL ages (at 1σ confidence) for Hastings Bank.

Seaward progradation of sediment deposited in a shoreface environment has been interpreted from seismic profiles calibrated with lithological information from vibrocore records (Chapter 4). OSL ages from these shoreface sediments indicates the shoreline was prograding between 8.4 ± 0.2 ka and 7.8 ± 0.2 ka (Fig. 7.2a). This corresponds to a period of rapid post-glacial sea-level rise when globally, the rate of relative sea-level rise was ca. 13m/ka (Smith et al., 2011). One of the most significant climatic events during this time period is the 8.2 ka cooling event driven by collapse of the Laurentide Ice Sheet and input of freshwater discharge into the North Atlantic Ocean (Barber et al., 1999). Estimates of the total volume of water released into the North Atlantic remain uncertain (Kendall et al., 2008) but are considered to have been significant enough to contribute to global eustatic sea-level rise, with increasingly more evidence for a 'sea-level jump' associated with the 8.2 ka event, being uncovered in sedimentary archives around the world (e.g. Tornqvist et al., 2004; Hijma and Cohen, 2010). Chronometric data obtained from Hastings Bank reveal that the shoreline was prograding over a timeframe that encompasses the 8.2 ka event. Landscape evolution at Hastings Bank may therefore have been partly conditioned by a low frequency, high magnitude sea-level event. Constraining such an event requires a highly resolved chronological framework and a record of ‘continuous’ deposition (Hijma and Cohen, 2010). This is more complicated at Hastings Bank as only five OSL dates are available and the record is much more fragmentary.

Whilst it may not be possible to link landscape evolution at Hastings Bank to an event scale sea-level jump, the shoreline was most likely prograding under some of the highest rates of relative sea-level rise experienced in the early Holocene. For a shoreline to prograde during transgression, a sediment supply greater than accommodation created by rising sea-levels is required (Clifton, 2006). Therefore, the amount of sediment supplied to Hastings Bank must have been considerable during the early Holocene. Fluvial input to the shoreline at Hastings Bank during the 8.2 ka event is unknown but expected to be low due to a small catchment size. Transport of sediment to the shoreline on a transgressive continental shelf is typically through reworking of offshore sources or recycling within the shore zone (Clifton, 2006). Considerable sediment resources lie offshore of Hastings Bank in the eastern English Channel (Chapter 6) where evidence of wave ravinement would imply at least some sediment was reworked into the shore zone by waves and/or tides during transgression. The volume of sediment deposited at Hastings Bank is large in comparison to other parts of the continental shelf where bedrock is exposed at the seabed. This may be a product of reworking either during, or after transgression. Alternatively, the amount of sedimentation at Hastings Bank and elsewhere in southeast England (e.g. Dungeness) may be related to the proximity of a bedload convergence zone in the Straits of Dover. A culmination of sediment transport vectors in this region may have maintained supply to the shoreline, despite rapid-rates of sea-level rise, thus enabling progradation.

There is evidence for a change in barrier behaviour from progradation (Fig.7.2a), to degradation and landward migration (Fig. 7.2c) (see Chapter 4 for full discussion). An OSL age calculated from washover sediments constrains barrier degradation to 5.3 ± 0.5 ka (LV407). Deposition through washover occurs during high energy conditions as waves overtop the crest of the barrier (Leatherman, 1977). Therefore, washover landforms must be at, or close to mean sea level, dependent upon the back-barrier morphology. At 5.3 ka, relative sea-level was at ca. -5 m OD according to a local relative sea-level curve (Fig. 7.1). This implies deposition of washover sediments occurred in water depths >10 m which contradicts the environmental interpretation established using seismic and core data. Sample LV407 is ca. 3 ka younger than other ages from the barrier complex and there is some concern about the reliability of the age produced (see section 7.4 for discussion). Therefore, this age should not be used to constrain the timing of barrier degradation.

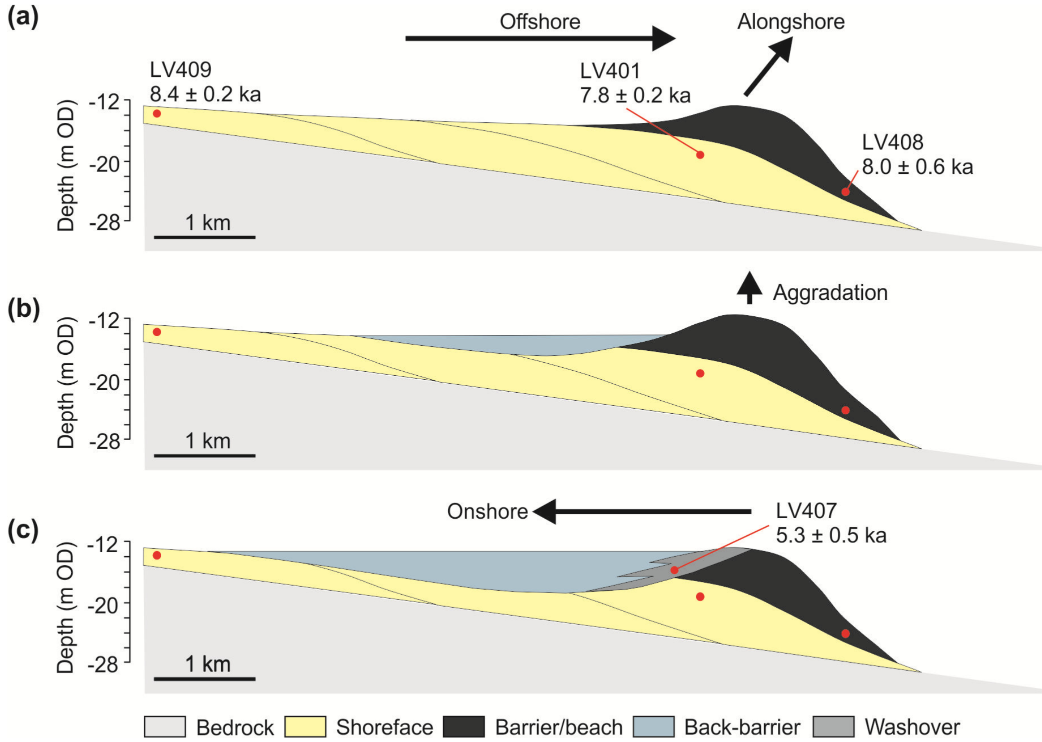

Figure 7.2: schematic illustration of coastal response to relative sea-level rise at Hastings Bank. Red dots show the location and depth of OSL samples. Full details of age calculation are given in Chapter 5, lab codes e.g. LV401 are used for reference. Black arrows indicate primary sediment transport vector. (a) progradation of the shoreline (b) progradation is limited by bathymetry and the shoreline aggrades creating a barrier island (c) the shoreline degrades and sediment begins to rollover into the back-barrier.

To summarise, the eastern English Channel continental shelf preserves the expression of fluvial processes operating during sea-level lowstand, as a composite network of bedrock valleys which act as containers for storing sediment deposited in shallow marine and coastal settings during transgression. Outside of the palaeovalley network the continental shelf is a bedrock platform as sediment is mobilised by strong tidal currents and transported onshore/alongshore, and to sinks coinciding with bedload convergence zones determined by tidal amphidromic points. Sediment transported onshore during transgression can be preserved as drowned shorelines under certain conditions, such as rapid rates of sea-level rise and high sediment availability. Overall, the data confirm sedimentary models of continental shelf stratigraphy with incision and deposition being principally driven by the relationship between accommodation created by base level and sediment availability. However, by chronometrically constraining the model, it is possible to resolve higher resolution controls on landscape development by linking the shelf to palaeoenvironmental archives elsewhere in the sedimentary basin.

7.2 PRESERVATION POTENTIAL

Question 2: *What is the preservation potential of landscapes on the continental shelf over the Quaternary period?*

The data presented in Chapter 6 demonstrate that on a paraglacial continental shelf, there is a bias towards preservation of landforms and sediments corresponding to the last glacial-interglacial cycle. Preservation of deposits associated with preceding stages is low as the continental shelf environment becomes a zone of sediment recycling over multiple sea-level cycles. In a subsiding basin, e.g. the southern North Sea, the stratigraphic record of the Quaternary has a greater preservation potential and has been widely used in palaeoenvironmental reconstructions (Sejrup 1987; Busschers et al., 2007; Meijer and Cleveringa, 2009; Hijma and Cohen, 2010). In an area experiencing gradual uplift, formation of terrace staircases preserves a fragmented record of palaeoenvironmental change. Locally, in the eastern English Channel, bedrock terraces are stepped and a relative sequence of events can be determined. Where sediment overlies these terrace surfaces, establishing a depositional age using OSL provides a framework to constrain erosion events (Chapter 6). However, not every erosional period is represented by vertical incision. On a relatively broad flat alluvial plain, such as the exposed continental shelf, erosion through lateral planation creates a bedrock strath terrace (e.g. Lewin and Gibbard 2010) that is the product of multiple phases. Separating a composite erosion surface into a series of discrete phases is problematic. Where sediments overly a distinct morphological feature, e.g. alluvial deposits within a channel meander, a link between erosion and deposition can be made. However, sediments overlaying terraces on the continental shelf are susceptible to reworking over several sea-level cycles creating a more complicated sedimentary record, with significant hiatuses, than envisaged in classical studies of fluvial response to changes in climate and sea level (e.g. Blum and Törnqvist, 2000).

A single OSL age of 176.6 ± 20 ka from sediments preserved in the eastern English Channel (Table 6.3) demonstrates that there is the potential to preserve remnants from preceding stages. In this case, the sediment was preserved as an alluvial terrace at the margin of a deep palaeovalley (SB Palaeovalley) that was incised during the last glacial period. Preservation of such deposits appears to be rare. However, identification using stratigraphic concepts alone is difficult due to the high degree of variability and erosional truncation observed in both seismic and core records. Despite using the best available data to develop the stratigraphic framework presented in this thesis, to fully understand the preservation potential of landforms and sediments on the continental shelf, 3D seismic data combined with a wealth of chronometric data would be required.

Thus far it has been demonstrated that predicting the preservation potential of landscapes at the Quaternary timescale can be problematic. Using Hastings Bank as an example, the preservation potential of coastal facies over shorter timescales (10^3 yrs) can be assessed. Typically, coastal facies preserved in the rock record are the product of prograding shorelines during regression (e.g. Storms and Swift 2003; Hampson and Storms 2003; Armitage et al., 2004; Jackson et al., 2010). However, there is increasing evidence to suggest coastal facies, particularly those associated with barrier systems, can be partially preserved during transgression (e.g. Forbes et al., 1991; Roy et al., 1994; Storms et al., 2008; Hijma et al., 2010; Chapter 4). Present understanding of what determines preservation of transgressive coastal deposits offshore of a highstand shoreline is based on numerical simulations that consider the interactions between accommodation created by relative sea-level rise and sediment availability (Storms et al., 2002; Cowell et al., 2003; Storms and Swift, 2003). The stratigraphy preserved at Hastings Bank, constrained with OSL ages, presents an opportunity to test these models using geological data.

Using the landscape evolution model presented in Chapter 4, it is proposed that preservation of barrier deposits during transgression is a function of style of shoreline retreat, i.e. overstepping vs. rollover. This is conditioned by the rate of transgression, sediment availability and accommodation created by rising sea-levels and inherited bathymetry. At this stage there is no chronometric data available to constrain the timing of retreat. An age of 5.3 ± 0.5 ka was calculated for washover sediments providing a minimum age for barrier overstepping. However, according to relative sea-level data (Fig. 7.1) the barrier was submerged in water depths >10 m at this time suggesting overstepping occurred during an earlier phase of transgression. Assuming wave base was similar to that observed today at the coast of south-east Britain, i.e. <1 m (Grochowski and Collins, 1994), according to relative sea-level data (Fig. 7.1) the barrier was beyond the limit of reworking by waves after ca. 7.5 ka. This indicates that the reliability of the age determined from washover sediments is questionable (see section 7.4).

Shoreline progradation occurred between 8.4 ka and 7.8 ka, and it is probable that overstepping occurred not long after this phase of progradation when sediment availability remained high enough to prevent reworking of the shoreface. It is not possible to resolve inflections in the rate of relative sea-level rise over this time period, such as those associated with the 8.2 ka event, using the data presented in this thesis. However, by assuming no major changes in the rate of relative sea-level rise over the lifetime of the barrier (ca. 1 ka), it is important to consider the style of retreat and thus preservation potential of coastal facies in terms of 'coastal resilience', i.e. the self-organising ability of the coast to respond dynamically to external drivers in a sustainable manner (Klein et al., 1998). This is contrary to common preconceptions where high 'resilience' is used to describe an immobile, morphologically robust landform, i.e. one that does not respond to change dynamically (e.g. Long et al., 2006). Here, as an alternative, the term 'inertia' is used to define response, in terms of mobility, of coastal landforms to changes in external agents. Prior to initial overstepping ('sediment surplus' Chapter 4) the barrier was resilient to change, as demonstrated by breaching and internal reworking of sediment to compensate for accommodation in the back-barrier environment. Despite being resilient, the barrier had high inertia and was static due to obstacles created by basement topography. A morphological threshold was reached when the back-barrier was filled and the barrier switched state to one of low (or dynamic) resilience and low inertia (rollover). However, the barrier did not maintain this state of resilience during retreat and phases of 'sediment deficit' overstepping represent periods of relatively higher resilience. Whilst rising sea-level is an absolute requirement for barrier overstepping, changes in the mode of resilience driven by internal response to this forcing agent, can influence the style of barrier retreat and preservation potential of coastal facies.

The preservation of landforms and sediments on the continental shelf in response to repeated sea-level cycles at the Quaternary timescale has been established. However the persistence of these landforms in the future and their preservation potential in the rock record is low in a basin that is not subsiding. A relative sea-level fall would expose the continental shelf and fluvial and terrestrial processes would rework any existing sedimentary records. Given the low preservation potential of sediments from preceding glacial-interglacial cycles, Weichselian to Holocene environments would be removed from the stratigraphic record or, at best, highly reworked. Where subsidence is negligible, the best means of preserving a sedimentary record is through vertical incision and the creation of terrace staircases, driven by faster rates of uplift or increasingly lower base-levels. Identification of terraces would require a morphological perspective of the erosion surface, which can be achieved in the sub-surface using 3D seismic data. It is expected that Quaternary continental shelves in paraglacial settings will be represented in the stratigraphic record by an erosion surface that encompasses >2 Ma of geological history. This surface would be the product of multiple processes operating over high frequency, high magnitude climate and base-level changes. However, extracting this information will be extremely difficult and a bias towards the sedimentary processes operating during the final stages of formation will always remain.

In conclusion, sedimentary and erosional landscapes preserved on a non-subsiding continental shelf are biased towards the processes operating in last glacial-interglacial cycle due to high degrees of reworking and modification, driven by dramatic fluctuations in sea-level at this timescale. The record is generally fragmented. However, the results demonstrate that it is possible to preserve remnants of preceding stages. Preservation potential is the greatest where valley incision creates terrace staircases. Erosion surfaces are composite and reflect multi-phase processes operating over long periods (10^4 yrs) of time. Predicting preservation potential is problematic as sedimentary regimes vary spatially across the shelf and can be influenced by local conditions such as topography. The results demonstrate that it is possible to preserve coastal landscapes during transgression thus changing perceptions of coastal response to relative sea-level rise. Hastings Bank may be one of the most exceptionally well preserved examples of a drowned barrier complex identified to date.

7.3 'CATASTROPHIC' VS 'NORMAL' PROCESSES

Question 3: *What is the relative significance of 'catastrophic' and 'normal' processes in shaping palaeovalleys in the eastern English Channel?*

Ongoing discussions in the published literature regarding the palaeogeographic evolution of the English Channel focus on the timing and mechanism of breaching at the Straits of Dover (see Chapter 2 for a review). It has been proposed that formation of the palaeovalley network in the eastern English Channel was directly influenced by the same process operating during breaching (Smith, 1985, Gibbard et al., 1988; Gupta et al., 2007).

Therefore, by understanding the timing and nature of processes operating in the eastern English Channel (Chapter 6), it may be possible to test conflicting hypotheses currently proposed to explain breaching at the Straits of Dover, i.e. ‘catastrophic’ flooding (Smith, 1985; Gibbard, 2007; Gupta et al., 2007), vs. ‘normal’ fluvial down-cutting (Dingwall, 1975; Gibbard et al., 1988; Busschers et al., 2008; Westaway and Bridgland, 2010).

The erosional morphology of the Northern Palaeovalley has been interpreted as the product of catastrophic flooding through breaching at the Straits of Dover (Gupta et al., 2007). The Northern Palaeovalley has long been recognised as a bedrock feature that is largely devoid of sediment fill (Hamblin et al., 1992). Analysis of seismic data provided by aggregate industries revealed pockets of sediment preserved at the margins of the Northern Palaeovalley that were targeted for chronological sampling (chapters 5 and 6). The sediments overlie two regionally extensive erosion surfaces referred to as T4 and ME in Chapter 6. The elevation of T4 correlates to the bedrock bench identified by Gupta et al. (2007), and ME represents the base of the Northern Palaeovalley. This stepped terrace-like morphology was interpreted as evidence for at least two episodes of flood erosion (Gupta et al., 2007).

Sediments overlying surface T4 (i.e. the bedrock bench) were identified as remnants of mass wasting at the base of a slope and an OSL age of 17.9 ± 0.7 ka places deposition during the last cold stage (MIS 2) (Chapter 6). These deposits are the result of periglacial weathering of a slope and are not associated with the processes that led to formation of surface T4. Therefore, the OSL age can only be used as a minimum age constraint, suggesting erosion occurred prior to ca. 18 ka. Sediments overlying surface ME (i.e. within the Northern Palaeovalley) were interpreted as part of a laterally accreting point bar that was active between 15.8 ± 0.9 ka and 17.1 ± 0.8 ka (Chapter 6). These sediments suggest that ‘normal’ fluvial regimes operated in the Northern Palaeovalley during the last cold stage (MIS 2).

As catastrophic flooding has been linked to MIS 12 (Toucanne et al., 2009a), there is a possibility that the Northern Palaeovalley was sculpted by ‘catastrophic’ floods and then later occupied by fluvial systems. However, to preserve a flood morphology, post-flooding ‘normal’ fluvial processes, i.e. those operating in MIS 2, would require limited erosive capabilities only, which contradicts present models of fluvial behaviour in response to climate and sea-level change (Blum and Törnqvist. 2000; Vandenberghe, 2008; Gibbard and Lewin, 2009). In addition, concordance of seismic reflectors with the erosion surface at the base of the Northern Palaeovalley implies fluvial processes are at least partly responsible for incision. The evidence presented in Chapter 6 clearly shows that fluvial processes played a significant role in the formation and modification of the Northern Palaeovalley thus contradicting the conclusion by Gupta et al. (2007) that the morphology is the product of two discrete flood events. This has implications for any calculations of palaeodischarge that were based on the topography as preserved today, making the statement that the flood events are "some of the largest megafloods on Earth" (e.g. Gupta et al., 2007), questionable.

The research carried out in this thesis has revealed evidence for incision by 'normal' fluvial processes within the Northern Palaeovalley during MIS 2. If formation of the Northern Palaeovalley was directly linked to the processes responsible for erosion of the land bridge at the Straits of Dover, according to the chronometrically constrained stratigraphic model presented in this thesis (Chapter 5), breaching occurred during, or after MIS 4, and prior to, MIS 2. Alternatively, If erosion of the eastern English Channel palaeovalley network as a whole was linked to the processes operating at the Straits of Dover, then breaching is expected to have occurred during, or prior to, MIS 6. There is no evidence of the processes that occurred during MIS 12, i.e. the time period proposed for initial breaching (Gibbard et al., 1988; Toucanne et al., 2009a), which questions the assumption that the palaeovalley network in the eastern English Channel was sculpted by the same processes operating at the Straits of Dover during breaching. However, an absence of evidence cannot be interpreted as an absence of process. At the glacial-interglacial timescale, continental shelf environments are highly susceptible to reworking and modification (see Chapter 6). It is highly probable that any evidence of the processes operating during MIS 12 has been destroyed making it difficult to understand the nature and timing of the mechanism that led to breaching at the Straits of Dover. Constructional bedforms created during megaflood events are of considerable size and volume, e.g. bedform wavelengths >230 m and heights of up to 20 m (Carling et al., 2009b). There is no evidence of such landforms in the eastern English Channel. If breaching was driven by a 'catastrophic' flood during MIS 12, this raises questions about the preservation potential of low frequency, high magnitude events in the stratigraphic record. Further, the results presented in this thesis focus on the eastern English Channel only, and similar high resolution integrated studies would be required elsewhere on the continental shelf to resolve ongoing debates. For example, French territorial waters and the Weald-Artois anticline, where a catastrophic breaching would presumably have formed a through-going incision surface into the southern North Sea.

Despite this, it is possible to conclude from the results presented in this thesis that formation of the Northern Palaeovalley was not solely linked to 'catastrophic' flooding and has at least been partly sculpted by 'normal' fluvial processes.

Thus far this discussion has used the terms 'catastrophic' and 'normal' processes without definition. The term 'catastrophic' was adopted after Gupta et al., (2007) who used megaflooding as an explanation for isolation of Britain from mainland Europe. The term megaflooding was employed by Baker (1997) to describe outburst flooding associated with Late Pleistocene ice sheets of North America and Eurasia, where peak discharges are expected to exceed 10^5 m^3 s^{-1} (Baker, 2009). Estimates of peak discharge for the English Channel flood events range between 0.2 x 10^6 m^3 s^{-1} and 1 x 10^6 m^3 $s^{-1,}$ thus confirming their classification as megafloods (Gupta et al., 2007). However, as demonstrated previously in this section, the assumptions upon which these calculations are based are flawed and peak discharges are expected to be much lower.

The definition of a catastrophic event is unclear across different temporal and spatial scales but they are commonly referred to as instantaneous events of significant magnitude (Stevenson, 2010). To complicate the matter further, the definition of instantaneous at different timescales varies. For example, instantaneous flooding over short timescales (years) may occur in a matter of days, i.e, widespread flooding due to prolonged periods of high rainfall. Alternatively, flooding due to collapse of major ice sheets at the end of the last glacial period (Baker, 1971) would also be considered instantaneous at the 10^3 yrs timescale.

From a long-term geological perspective 'catastrophic' processes are considered to involve energy levels several orders of magnitude greater than 'normal' or background processes (Reading, 1996). Therefore, to understand 'catastrophic' processes, there is a need to understand the magnitude and frequency of 'normal' processes. In continental shelf environments, the present is not the key to the past at the glacial-interglacial timescale and there are no modern analogues of cold climate emergent shelves. Therefore, little is known about 'normal' processes and the preservation potential of associated landforms/sediments in the stratigraphic record. The data presented in Chapter 6 have been used to characterise 'normal' processes on a paraglacial continental shelf. Here, we have demonstrated that multiphase processes over a long period of time (at least 200 ka) can produce a landscape that has a similar morphological character to one produced instantaneously by a catastrophic event e.g. the Channelled Scablands (Bretz, 1969), and present an example of equifinility in geomorphic systems. However, there is a need to greatly improve our understanding of continental shelf environments if we are to further attempt to define what is 'normal' and what is 'catastrophic'.

The data presented in this thesis have not resolved the debate surrounding the timing and processes that drove initial breach at the Straits of Dover. It is possible to conclude that the Northern Palaeovalley was at least modified by 'normal' fluvial processes during MIS 2 therefore disputing the hypothesis presented by Gupta et al. (2007) that it formed through catastrophic flooding. There is no sedimentary or morphological evidence preserved on the continental shelf of a catastrophic flood, and there is a bias in the record towards the processes operating during the last glacial-interglacial cycle, making it difficult to fully test the hypothesis using drowned landscapes of the eastern English Channel.

7.4 DATING CONTINENTAL SHELF SEDIMENTS USING OSL

Question 4: *Are sediments preserved on continental shelves suitable for Optical Stimulated Luminescence dating?*

The application of OSL dating to sediments recovered from the continental shelf in the eastern English Channel is presented in Chapter 5. A fundamental requirement of OSL dating, whether it is applied in terrestrial or marine settings, is obtaining suitable material for laboratory analysis (Duller, 2008b). This is achieved if; (i) sediments comprise quartz or feldspar grains; (ii) those grains produce luminescence; (iii) the sediment is exposed to daylight during transport and deposition; (iv) changes in environmental conditions pos-deposition are quantifiable, and; (v) the sediment is sampled without exposure to daylight.

Long-term denudation of the continental shelf in response to fluctuating sea-levels characteristic of the Quaternary period, has provided an abundant supply of quartz to depositional systems operating on the shelf. Continental shelves are an important conduit in the transport of sediment from source to sink. Consequently, their hinterlands occupy a large proportion of the sedimentary basin and can include complicated geologies. As the sensitivity of quartz to luminescence is partly controlled by rock type (Sawakuchi et al., 2011), it is highly likely sediments preserved on the continental shelf will comprise quartz grains with inherent luminescence. Luminescence sensitivity is further enhanced through sediment recycling and reworking by fluvial, coastal and marine processes over repeated sea-level cycles (e.g. Chapter 6).

Sediments preserved on the continental shelf are not necessarily deposited in a shallow sea setting. During sea-level lowstand the continental shelf becomes a fully terrestrial environment and sediments transported over the shelf during this time have the potential to be exposed to daylight, i.e. bleached. Sediments transported and deposited in aeolian, fluvial, coastal, shallow marine and colluvial environments have the potential to be sufficiently bleached (Wintle, 1993; Wallinga, 2002; Bateman, 2008; Jacobs, 2008) and are therefore suitable for OSL dating. Targeting sediments for OSL dating requires confidence in interpretations of depositional environment. This can be achieved through integration of marine geophysics and core data as demonstrated in chapters 4 and 6. If suitable depositional environments are targeted for OSL dating, there is the potential for quartz to be sufficiently bleached to permit the application of OSL dating.

Once quartz is buried, the principals of OSL dating assume that there are no post-depositional changes in sedimentary environment. In continental shelf environments, dramatic fluctuations in sea-level can repeatedly expose and submerge a sediment body, leading to changes in dose-rate history that will ultimately affect the age estimate. This is less of a problem for sediments deposited during the Late Glacial period as they have been submerged in water depths of >30 m for at least 10 ka. For sediments that have experienced repeated sea-level cycles, the changes in water content can be modelled and the resulting variable dose-rate history can be incorporated in the uncertainty estimate of the OSL age.

Extracting sediment from the continental shelf for OSL dating without exposure to daylight can be achieved using opaque liners during vibrocoring. If sediment is recovered in a transparent liner, as long as there is no evidence of disturbance during recovery, the core can be sampled under red light, and the outer 1 cm removed to ensure no bleached grains are incorporated into the OSL sample.

Assuming the above criteria are met, for continental shelf sediments, the extraction of quartz and measurement of OSL in the laboratory should follow standard protocols for OSL dating (Aitken, 1998; Wintle and Murray, 2006, Mauz et al., 2002).

It is important to assess the suitability of OSL in dating continental shelf sediments according to the reliability of the age that is produced. Where possible, the reliability of OSL ages can be assessed using other chronometric information. In continental shelf settings where organic sediments are rare, ^{14}C dating of shell material is an alternate chronometric tool. However, inconsistency between OSL and ^{14}C ages from sediments preserved in the eastern English Channel (Wessex Archaeology, 2008) raises questions about the reliability of one or both of the techniques. Reported ^{14}C ages are consistently younger than OSL ages. Therefore, the inconsistency cannot be explained by the marine reservoir effect (Mangerud, 1972). Comparison of marine shell ^{14}C ages with OSL ages from sediments recovered from the southern North Sea show a similar pattern that is considered to result from uptake of young carbon through secondary precipitation of aragonite post-mortem (Busschers et al., 2011). It was not possible to resolve this matter using sediments recovered for this research due to the lack of suitable shell material for ^{14}C dating, i.e. preservation of specimens in situ with no sign of post-mortem transport and reworking. However, until this phenomenon has been investigated further, the use of ^{14}C dating of marine shell to test the reliability of OSL ages from continental shelf sediments is not recommended.

Where no independent chronometric constraint is available to test the reliability of OSL ages, the straigraphy of sediments in relation to relative sea-level history can be used as a benchmark. At the basin-wide scale, by assuming; (i) fluvial incision occurs during sea-level fall to low-stand; (ii) valleys fill with sediment during transgression, and; (iii) the sequence is repeated over each sea-level cycle, (Catuneanu, 2006), a relative age can be estimated at 10^3-10^4 yr timescales. According to this assumption, the OSL ages presented in Chapter 5 are remarkably consistent with the proposed stratigraphic model suggesting ages are reliable. However, higher resolution stratigraphic analysis, such as that carried out at Hastings Bank (Chapter 4), and multiple OSL ages can highlight inconsistencies between ages even over shorter (10^2 yr) timescales. As discussed previously there is some ambiguity surrounding the reliability of the age produced from sample LV407 (see section 7.1 and 7.2). Relative sea-level data (Waller and Long, 2010) and interpretations of depositional environment (Chapter 4), would suggest the age is too young. Sample LV407 demonstrated a wide distribution of D_es (Fig. 5.5) reflecting incomplete bleaching of quartz and was relatively insensitive to luminescence (Fig. 5.3). Statistical assessment of D_es led to the application of the Minimum Age Model (MAM) following the decision protocol of Bailey and Arnold (2007). The Minimum Age Model attempts to target the lowest D_e component within a distribution that is usually considered the fully bleached proportion of grains within a heterogeneously-bleached distribution (Galbraith, et al., 1999). In other words it truncates the distribution towards lower D_es and gives a younger age than would be estimated using the Central Age Model, i.e the weighted average of mean D_e. If low De estimates within a distribution are related to experimental or other factors not related to bleaching, the application of MAM will result in an artificially low age estimate. Given the stratigraphic details and sea-level data and OSL properties, the age calculated for sample LV407 is considered unreliable – probably resulting from artificially low D_e estimates due to the low OSL sensitivity. As an alternative, if the Central Age Model was applied to sample LV407, the resulting age would be 6.6 ± 1.5 ka which is more realistic given other age dates and the local stratigraphy.

To summarise, continental shelf sediments have the potential to provide suitably sensitive quartz that over glacial-interglacial cycles, has the potential to be sufficiently bleached to enable age determination using OSL. Using bathymetry and sea-level data, it is possible to reconstruct changes in cosmic dose history over long periods of time. It is difficult to test the reliability of OSL ages in continental shelf settings using other chronometric tools such as ^{14}C. Using stratigraphic models constructed from high resolution geophysical data is a suitable alternative at the glacial-interglacial timescale. However, resolving higher resolution discrepancies between ages is more problematic. Despite this, OSL is considered an important tool for improving understanding of Quaternary environmental change using drowned landscapes on the continental shelf.

7.5 WIDER IMPLICATIONS AND FUTURE RESEARCH

The research presented in this thesis, whilst somewhat specific to the English Channel, has contributed to knowledge of landscape evolution in continental shelf environments, over glacial-interglacial cycles. More specifically, the research has uncovered a history of sedimentary processes, and by chronometrically constraining phases of deposition, it has been possible to couple process-response to major climate and sea-level cycles, and resolve higher frequency, more localised controls on landscape development. Using the stratigraphic framework presented in this thesis, the imprint of different sedimentary processes on the continental shelf, i.e. erosion or deposition, has been examined. Further, the persistence of landscapes, and preservation potential of erosional and depositional records, in a shelf setting over multiple sea-level cycles, has been addressed. Overall, the research has demonstrated the complexity and multi-phase character of continental shelf systems using a Quaternary example, thus confirming why shelf environments are so poorly represented in sequence stratigraphic models (e.g. Catuneanu, 2006). Given the range of allocyclic and autocyclic controls on continental shelf evolution operating over relatively short timescales (10^3 yrs), it may not be possible to develop a universal stratigraphic model for the continental shelf environment. However, the research presented in this thesis can be used to provide a conceptual model of sedimentary processes operating on the continental shelf, and more importantly the archives these processes may or may not leave behind, which is fundamental for the study of sedimentology and drowned landscape evolution.

The chronometrically constrained stratigraphic model presented in this thesis was used as a framework to reconstruct palaeogeographic configuration of the eastern English Channel over the last ~200 ka. This has vastly improved understanding of Quaternary history of the English Channel and provided a basis to start addressing questions surrounding the timing and mechanism of breaching at the Straits of Dover. The research did not find any direct evidence to support either of the hypotheses currently under debate (e.g. Smith, 1985; Gupta et al., 2007; Busschers et al., 2008). However, a minimum age for breaching, determined using OSL, was established, and evidence for non catastrophic evolution of the palaeovalley complex was revealed. This research highlighted the fragmentary nature of sedimentary archives on the continental shelf and the difficulties in using them resolve sedimentary process-response at timescales >100 ka. It has been demonstrated that sedimentary archives preserved at the continental shelf edge break can document changes in climate, sea-level and major drainage configurations (e.g. Toucanne et al., 2009a). Therefore, rather than searching the continental shelf, i.e. an area of sediment bypass, for answers to ongoing debates, future research should focus on exploring the depositional records at the shelf margin (e.g. Eynaud et al., 2007).

It has been demonstrated that over shorter timescales (10^3 yrs), continental shelves have the potential to provide a wealth of information about landscape response to climate and sea-level change. The drowned barrier complex at Hastings Bank is a rare example where coastal facies are preserved during transgression. The fact that such a landscape exists, raises questions about current understanding of coastal response to rapid relative sea-level rise (e.g. Fitzgerald et al., 2008) and preservation potential of coastal facies in the rock record (e.g. Storms and Swift, 2003). The research presented in this thesis started to examine the controls on barrier behaviour during relative sea-level rise. OSL ages suggest that the barrier developed under rapid rates of sea-level rise, possibly associated with the 8.2 ka climatic event, during the early Holocene. However, the results also demonstrated that local conditions such as inherited topography played a significant role in determining barrier behaviour. This highlights the need to investigate the relative contribution of external (e.g. rate of sea-level rise and sediment supply) and internal factors (e.g. morphodynamics) on coastal landscape development further. Hastings Bank has the potential to provide chronometrically constrained geological data for testing numerical models of coastal landscape response to relative sea-level rise (e.g. Storms et al., 2002). This can be achived by obtaining multiple dates to provide a spatially and temporally constrained framework for the interpretation of landscape evolution (e.g. Roberts and Plater, 2007). Furthermore, by establishing a link between the Hastings Bank and Dungeness, it will be possible to assess spatial, as well as temporal evolution of gravel dominated coastal systems as a means to better understand their behaviour in response to future projections of climate and sea-level change.

Finally, the first attempt at dating a variety of drowned landscapes using OSL was carried out as part of this research – an approach that is essential for interpreting the sedimentary and morphological evidence preserved on continental shelves. The methodological approach presented in this thesis can be used as a guide by others to extracting sediment from drowned landscapes for dating using OSL. There are questions surrounding the reliability of some ages produced which needs to be investigated further. This can be achieved by improving precision and accuracy of the OSL dating technique (e.g. Bailey, 2004). Alternatively, the reliability of ages could be tested using an independent chronometric tool such as ^{14}C dating. However, the data presented in this thesis demonstrate that organic sediments are rare in continental shelf settings and there is a high likelihood of reworking an incorporation of old carbon. Therefore, there is a need to explore the application of other dating techniques to drowned landscapes if we are to fully assess the reliability of OSL ages. OSL dating proved suitable in resolving the timing of depositional events on the continental shelf. However, one of the major limitations of the research carried out in this thesis was the inability to date erosion events. This is a common problem across a range of landscapes. In terrestrial systems it is being tackled using cosmogenic radionuclide dating (e.g. Cockburn and Summerfield, 2004) and thermochronometry (e.g. Binnie et al., 2008). The suitability of these techniques in dating drowned landscapes needs to be tested.

There is still a great deal to be resolved in unravelling the channel networks preserved in the eastern English Channel. This may be achieved using 3D seismic data. However, given the complexity of drainage networks and the multi-phase development of the fluvial system, this may not be possible. The influence of basement topography and underlying land-level movements has not been fully examined in this thesis. This can be developed in the future by establishing a link between the palaeovalleys of the eastern English Channel and major drainage networks in Northwest Europe, i.e. the Thames and Rhine.

The emerging archaeological and palaeoenvironmental evidence from shelf seas (e.g. Doggerland) highlights the potential for the work presented in this thesis to be applied in the study of past human-environment interactions, exploring how different cultures and ways of living may have emerged in relation to the drowning of occupied landscapes. Indeed, the ongoing testing of ‘Noah’s Flood’ as a marine incursion in other parts of the world is likely to have wider material to draw on in relation to the unexpected and permanent drowning of settled land.

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Appendix A

Emu Limited
Head Office
1 Mill Court
The Sawmills
Durley
Southampton SO32 2EJ
UK

Tel: +44 (0)1489 860050
Fax: +44 (0)1489 860051

Eastern English Channel PhD Research Lines

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Report No.	: 09/J/1/02/1538/0958		
Emu Job No.	: J/1/02/1538		
Client Name	: Hanson Aggregates Marine Ltd		
Client Contact	: Rob Langman		
Project Manager	: Anthony Buckley		
Hydrographic Surveyors	: Ashley Spratt, Adam Cross, Brian Gamet		
Marine Geophysicists	: Alex Elliott, Anthony Buckley,		
Data Processor	: Brian Gamet		
GIS	: David Lonsdale		
		Signature	Date
Report written by	Brian Gamet		5/2/2010
Report checked by	Ben Rainbow		5/2/2010
Report authorised by	Huw Powell		5-2-10
Report Status	FINAL		
Issue Date	03/02/2010		

Client	Hanson HEIDELBERGCEMENT Group	Hanson Aggregates Marine Ltd Burnley Wharf, Marine Parade, Southampton SO14 5JF
Contractor	EMU	Head Office, 1 Mill Court, The Sawmills, Durley, Southampton Hampshire, SO32 2EJ Tel: +44 (0) 1489 860050 Fax: +44 (0) 1489 860051 mail@emulimted.com www.emulimited.com

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EXECUTIVE SUMMARY

Emu Ltd was commissioned by Hanson Aggregates Marine Ltd to carry out a geophysical survey of three lines in the Eastern English Channel (EEC), approximately 30 km east and west of Eastbourne, to support research for a PhD project. The survey included the collection of high-resolution boomer sub-bottom profiling data, multibeam bathymetry, and high-resolution sidescan sonar data over a survey line track length of approximately 47 km.

Mobilisation of the vessel *Emu Surveyor* was carried out in Eastbourne, from the 8th-9th December 2009. Equipment used included a fully motion-aided Reson 8125 multibeam system, an Edgetech 4200 dual frequency sidescan sonar system and an Applied Acoustics boomer system. A POSMV motion reference unit receiving differential corrections was used for horizontal positioning of the vessel. Tidal data was acquired using a Leica 1200 GPS system and post-processed with RINEX data.

Survey operations were carried out on the 16th December 2009, 05th January 2010 and on the 11th January 2010. Data processing, interpretation and reporting were completed at the Emu Limited head office in Durley, Southampton.

1 INTRODUCTION

1.1 Scope of work

The scope of work was outlined in proposal No. P/1/02/09/0905 and included the simultaneous collection of shallow, high-resolution boomer sub-bottom profiling data, together with multi-beam echo-sounder and high-resolution sidescan sonar data along the length of the three survey lines. Data has been delivered in digital format with this report.

The methodologies carried out to achieve these objectives have been presented in Section 2.0.

1.2 Location

The location of the three survey lines (presented in Figure 1.1) were in the Eastern English Channel (EEC), approximately 30 km east and west of Eastbourne. The survey lines were run in an approximately north-south orientation and totalled approximately 47 km in length.

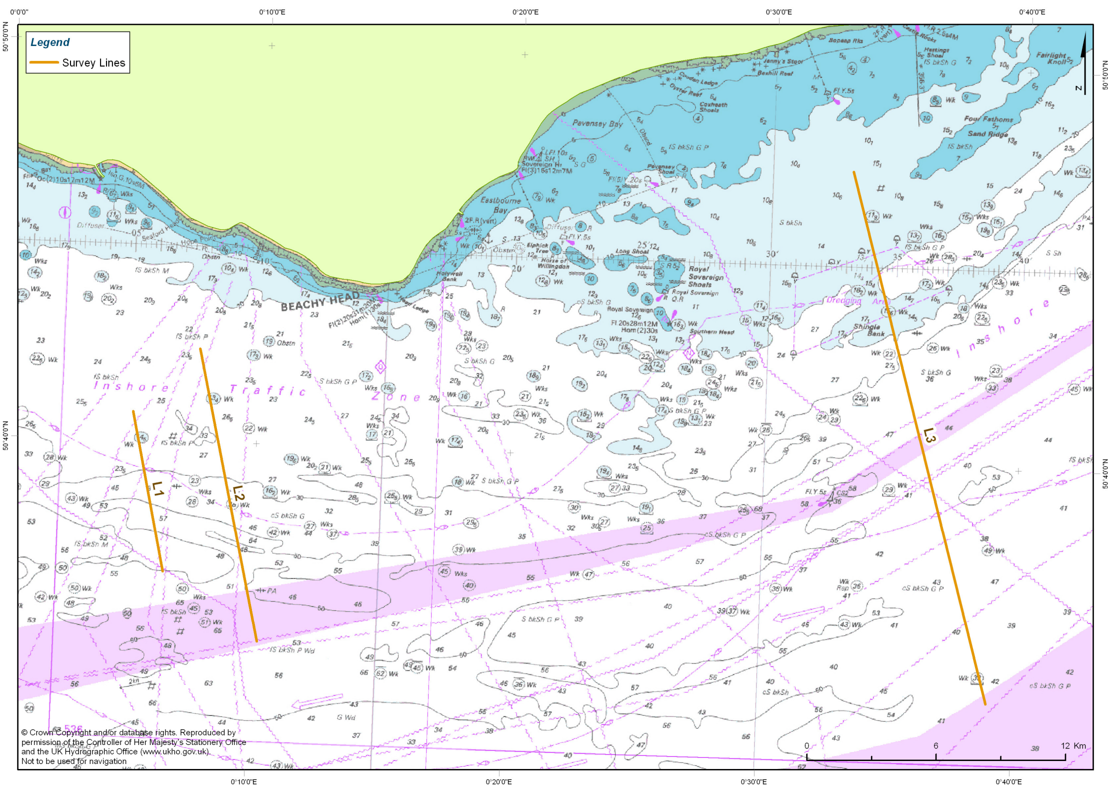


Figure 1.1 Survey Line Plan

Line number	WGS84				Length (km)
	Start Lat	Start Long	End Lat	End Long	
L1	0º 5' 6.19" E	50º40' 43.637" N	0 º 6' 30.683" E	50 º 36' 44.654" N	7.57
L2	0 º 10' 18.43" E	50 º 35' 4.138" N	0 º 7' 38.713" E	50 º 42' 21.689" N	13.88
L3	0 º 38' 59.55" E	50 º 34' 8.332" N	0 º 33' 8.555" E	50 º 47' 22.535" N	25.49

Table 1.1 **Coordinates of survey lines**

1.3 Summary of Events

Prior to the commencement of the geophysical survey, a Notice to Mariners was issued on the 9th December 2009 via email. This notice detailed the survey location, vessel, expected schedule and a description of the general purpose of the survey. Recipients of this notice included local fisheries organisations, local harbour masters, coastguards and vessel traffic authorities.

The geophysical survey was carried out on the vessel *Emu Surveyor*, a 12 m bespoke survey vessel owned and managed by Emu Limited.

Mobilisation of *Emu Surveyor* was carried out at Sovereign Harbour, Eastbourne, from the 8th to 9th December 2009. Survey operations were carried out on the 16th December 2009, 05th January 2010 and on the 11th January 2010.

Comprehensive logs were kept throughout the duration of the survey. Daily logs included details of survey activities, weather conditions, navigation and safety issues and have been presented in Appendix B. Daily progress reports were completed and issued to the Client throughout the survey.

Data processing and reporting were carried out at the Emu Limited head office in Durley, Southampton.

2 METHODOLOGY

This section includes a brief factual description of the methods used to achieve the project objectives. More detailed descriptions of specific survey techniques and procedures are contained within the Emu Limited Method Statement, numbers 8 and 9 (a component part of the Company's QA Manual - details of which can be inspected on request).

2.1 Horizontal Positioning

HORIZONTAL POSITIONING	
Requirement	**Application**
Provision of navigation information to on board sensors with an accuracy of 3-5 m.	A Hemisphere Crescent DGPS system received corrections from the EGNOS differential network via satellite and Trinity House differential stations. This enabled the location of seabed information collected by on board sensors to be determined with a high degree of accuracy, typically 2-3 m.
Data Collection	
Survey Dates:	16/12/2010, 05/01/2010 and 11/01/2010
Equipment Used:	Hemisphere Crescent DGPS R120 QINSy 8 hydrographic navigation system
Vessel:	*Emu Surveyor*
Methodology:	
The DGPS receiver was configured to receive corrections from the EGNOS differential network via satellite. A navigation error check was performed during mobilisation and details can be found in the Daily Logs in Appendix B. All relevant instrument offsets were measured before the survey commenced and entered into the QINSy 8 software.	

Navigation Settings			
Geodetic Parameters System Source (GPS)		Projection Parameters	
Spheroid	WGS 1984	System	UTM
Semi-major axis	6378137.000000	Zone	31 North
Semi-minor axis	6356752.314245	Central Meridian	3° E
Inverse Flattening	298.257223563	False Easting	500000
		Scale Factor	0.9996

Table 2.1 Summary of Horizontal Positioning Methodology

2.2 Swath Bathymetry Survey

SWATH BATHYMETRY SURVEY	
Requirement	**Implementation**
To determine seabed depths throughout the site.	In order to measure the depths of all parts of the seabed, a swath bathymetry system built up a series of strips of bathymetric data to either side of the vessel as it moved forwards. Each strip or "swath" laid side-by-side enabled the entire seabed to be surveyed.
Data Collection	
Survey Dates:	16/12/2010, 05/01/2010 and 11/01/2010
Equipment:	Reson Seabat 8125 multibeam system POS MV precision motion and attitude system Valeport Mini-SVP QINSy 8 acquisition, navigation and processing software Leica 1200 GPS system – Post-processed kinematic (PPK) tides
Vessel:	*Emu Surveyor*
Methodology: A series of acoustic pulses ("beams") were emitted perpendicular to the vessel track. The time it took each beam to return to the system was accurately measured to derive the seabed depth at each point of insonification using a profile of sound velocity in the water column. The resulting swath soundings provided high resolution information on the bathymetry of the seabed. Attitude and motion were measured by the POS MV unit which provided heave, roll, pitch and yaw data. This information was fed directly into the QINSy system giving real time bathymetric corrections. The swath system was calibrated prior to the survey with a standard patch test operation. This allowed, in each case, the calculation of fixed mounting variations for heading, pitch and roll. Post-processing was carried out using QINSy processing software. Relevant corrections and filters were applied including the patch test calibration results, removal of outliers with automatic and manual filtering and post-processing of tidal data. The cleaned data were gridded using a 1 m bin size and exported into an ASCII XYZ data file.	
Data Outputs	
<u>Digital Data</u> ASCII XYZ bathymetry data	

Table 2.2 **Summary of Swath Bathymetry Survey Methodology**

2.3 Sidescan Sonar Survey

<table>
<tr><th colspan="2">SIDESCAN SONAR SURVEY</th></tr>
<tr><th>Requirement</th><th>Application</th></tr>
<tr><td>Interpretation of variations in seabed type and identification of any objects that may present a hazard to dredging activity.</td><td>A high resolution dual frequency (120 kHz/400 kHz) sidescan sonar system provided high resolution acoustic images of the seabed. The configuration of the system, with wide vertical and narrow horizontal beam angles, enabled a swath of the seabed to be imaged by each pulse. Variation in backscatter intensity indicated changes in sediment type, bathymetry or the presence of seabed targets.</td></tr>
<tr><th colspan="2">Data Collection</th></tr>
<tr><td>Survey Dates:</td><td>16/12/2010, 05/01/2010 and 11/01/2010</td></tr>
<tr><td>Equipment Used:</td><td>Edgetech 4200 dual frequency sidescan sonar towfish & transceiver
SonarPro acquisition software
SonarWiz processing software</td></tr>
<tr><td>Vessel:</td><td>Emu Surveyor</td></tr>
<tr><td colspan="2">Methodology:

Sidescan sonar data were acquired along each the length of each survey line. Both high (400 kHz) and low (120 kHz) frequency channels were recorded digitally in both XTF and JSF formats. The sidescan sonar towpoint position was provided for navigation and cable-out values were logged throughout the survey. Layback values were calculated using cable-out values and logged fish depths. These values were applied during processing using SonarWiz software, along with gain corrections, to provide a position-corrected sidescan sonar mosaic.

Full QC procedures were adhered to throughout data collection and processing.</td></tr>
<tr><th colspan="2">Data Outputs</th></tr>
<tr><td colspan="2"><u>Digital Data</u>
Raw .XTF and .JSF file formats
Layback values provided in survey logs</td></tr>
</table>

Table 2.3 Summary of Sidescan Sonar Survey Methodology

2.4 Seismic Survey

SEISMIC SURVEY	
Requirement	**Application**
Collection of seismic data suitable for determining sub-seabed geology including aggregate resources.	A surface towed boomer system emitted a high frequency (1-4 kHz), low energy (100 J) pulse that allowed penetration into sub-seabed sediments for the detection of geological layers and units. Information about the sedimentary composition can be interpreted from the nature of seismic facies.
Data Collection	
Survey Dates:	16/12/2010, 05/01/2010 and 11/01/2010
Equipment Used:	Applied Acoustics boomer catamaran with 200J boomer plate Applied Acoustics CSP 1500J seismic energy source C-Products 8 element hydrophone streamer Coda Octopus DA2000 digital acquisition and processing system Octopus 120 thermal printer
Vessel:	*Emu Surveyor*
Methodology: Before the survey commenced the boomer system was tested in the site vicinity to establish the optimum, site-specific settings for the system. A power of 100 J was selected and a trigger interval of 250 ms with a recorded voltage range of ±1.25 V. The sweep time recorded within the digital data was set to 120 ms but the sweep time recorded on paper records was maintained at 80 ms. The boomer catamaran and hydrophone were maintained at 32 m astern throughout the survey. This layback was applied to online navigation and therefore applied to all digital and paper data. Fixes were generated by QINSy navigation software at 50 m intervals and recorded within digital and paper records. All settings and offsets have been recorded in online logs and can be provided on request. All data were logged digitally (.cod format) in the Coda Octopus DA2000 acquisition and processing system and printed online on an Octopus 120 thermal printer.	
Data Outputs	
<u>Digital Data</u> Coda (.cod) digital boomer files for all lines	

Table 2.4 Summary of Seismic Survey Methodology

3 POSITIONAL ACCURACY AND DATA QUALITY

The horizontal positioning data from the DGPS system were of good quality throughout the duration of the survey, with a positional accuracy of greater than 2 m and no drop outs in the EGNOS signal. Any seabed features present in the sidescan sonar data were estimated to have an accuracy of approximately ±10 m across track due to the manual layback method and the influence of environmental factors such as tidal currents.

The swath data collected were of good quality and any obvious noise present in the dataset has been removed with automatic and manual filtering. Relevant corrections and filters were also applied including the patch test calibration results, and tidal data within the QINSy processing software.

The PPK height data were processed in Leica Geo Office at five second intervals using the five nearest OS Net Active GPS RINEX stations. All data with a height quality of less than 0.2 m were selected and imported into Microsoft Excel for further processing. A smooth curve was then drawn through the PPK data and compared with observed tide data from Newhaven (British Oceanographic Data Centre). Due to the distance of the PPK data from the Newhaven tide gauge, a range and small phase difference was noted between the PPK data and the tide gauge. It was decided that the smoothed PPK data were a good representation of the tide after consulting co-tidal and co-range charts. These data were applied to the multibeam depth soundings.

All datasets are found to be of very good quality, this being assisted by generally good sea conditions at the time of survey, despite strong south-westerly winds.

4 QUALITY ASSURANCE

The geophysical survey was performed to the highest standards using the best equipment and experienced personnel. The survey data acquired offshore were of good quality and in all cases deemed to satisfy the requirements of the contract. Data collection and processing was conducted with great care and in accordance with Emu Limited’s Quality Management System which complies with the requirements of BS EN ISO 9001:2008.

5 HEALTH AND SAFETY

On the commencement of the geophysical survey a vessel safety briefing was attended by all survey personnel and crew. Emergency procedures were explained and the use of emergency equipment was demonstrated. Following changes in vessel personnel, additional safety briefings were carried out.

A safety plan and risk assessment was completed prior to commencement of the survey. All survey and crew members were required to read and sign the safety plan. This is available on request.

No reportable incidents occurred over the duration of the geophysical survey.

Appendix B

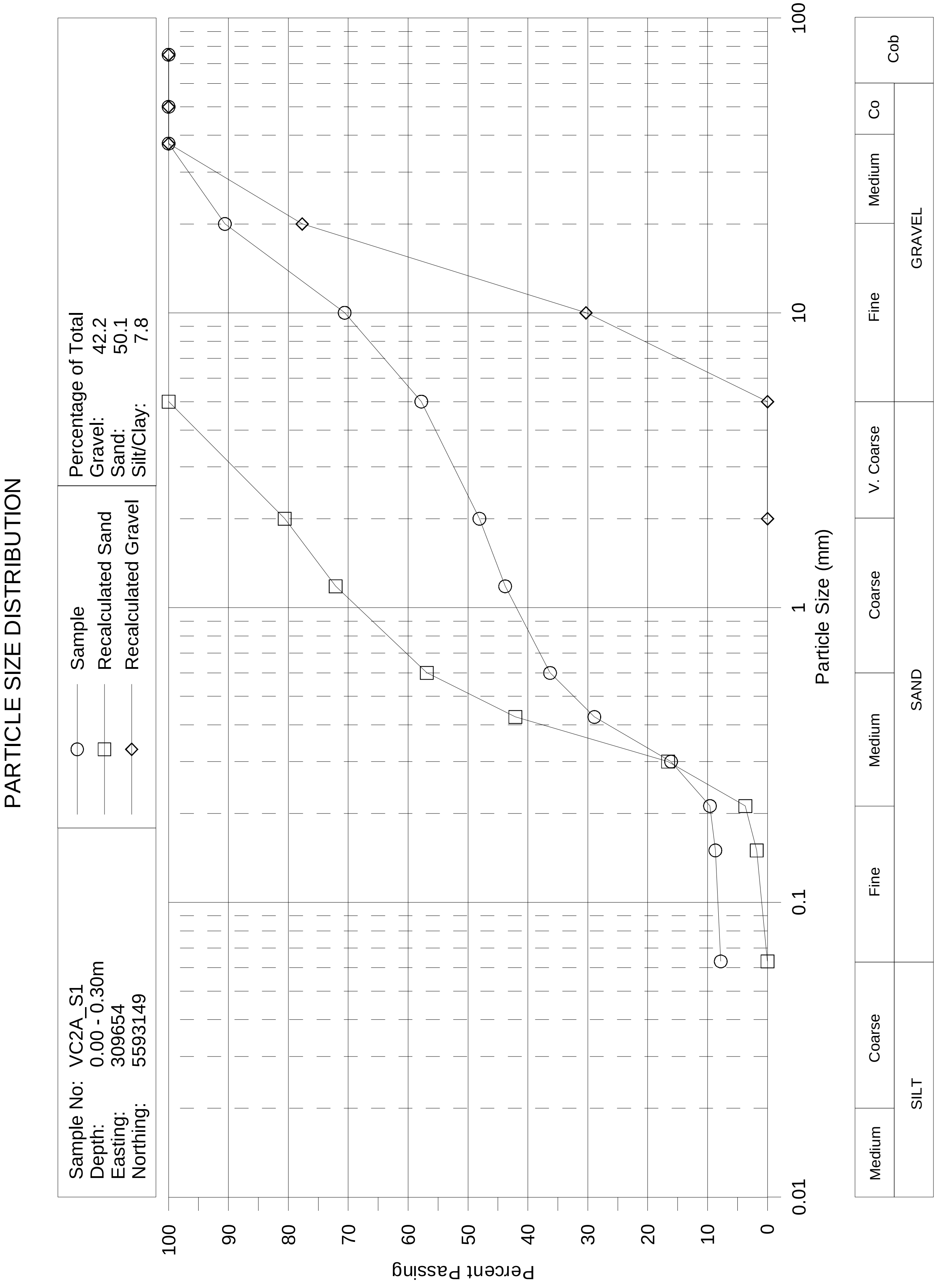
LOCATION: AREA 473 WEST		**DATE: 05-SEPT-03**	**VIBROCORE 2A**
LOGGED BY: GP	**COMPILED BY: CB**	**CHECKED BY: VG**	**E 309654** / **N 5593149**

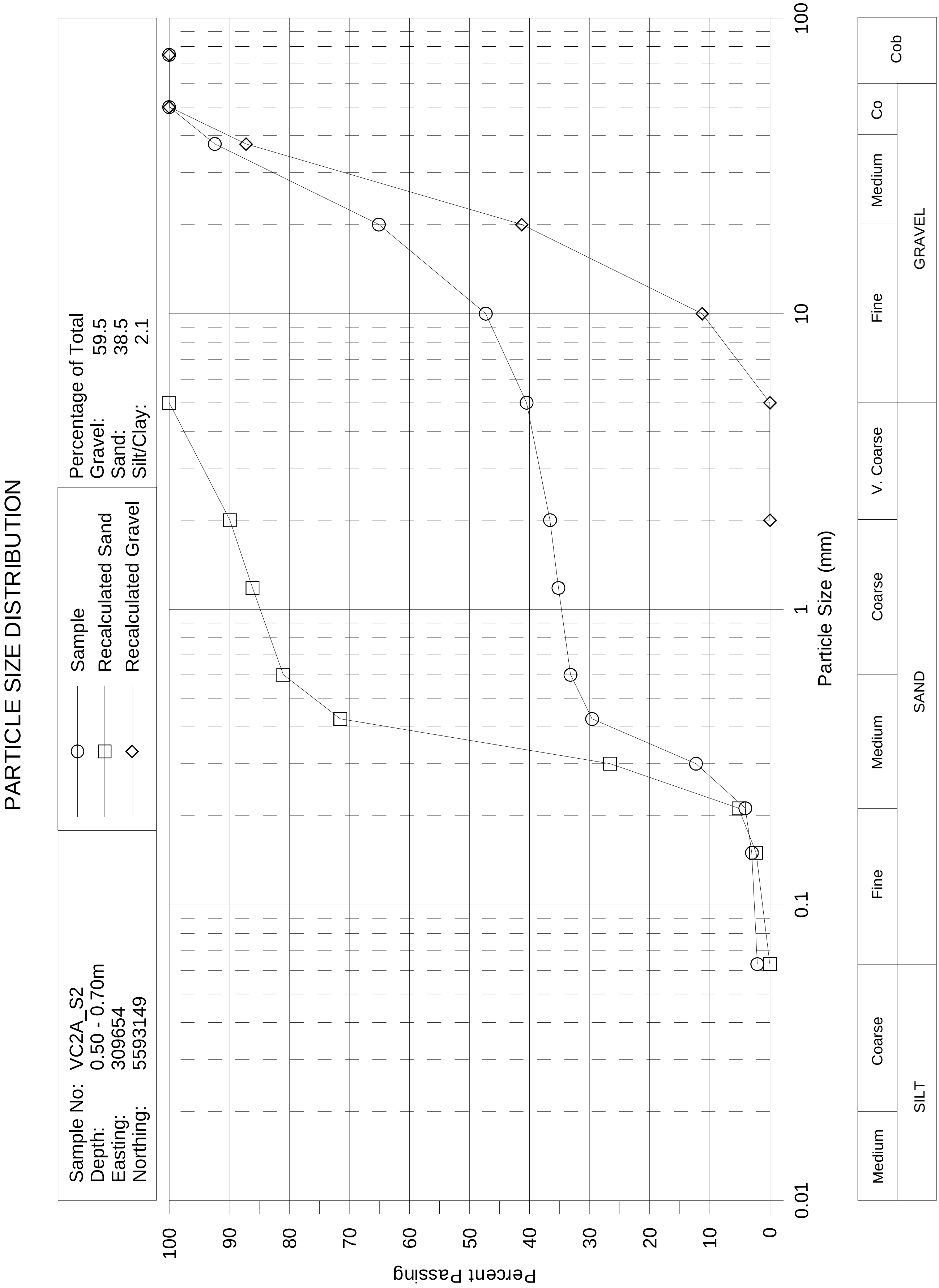
DEPTH (m)	DESCRIPTION	PSD TAKEN	GRADING SUMMARY (%) ALL SAMPLE <63µm	63µm - 5mm	5 - 37.5mm	>37.5mm	SHELL % in ALL SAMPLE 2 - 5mm	5 - 20mm	20 - 40mm	40 - 60mm
0.40	Light yellowish brown (2.5Y 6/4) shelly silty SAND and GRAVEL (Shell fraction is sand to medium gravel sized, gravel fraction is angular to rounded flint, conglomerate, chalk, granite, sandstone, limestone and quartz, sand fraction is medium to very coarse)	Yes	7.8	50.1	42.2		4.0	10.9	2.5	
0.74	Light yellowish brown (2.5Y 6/4) slightly shelly slightly silty very sandy fine to coarse angular to rounded flint, sandstone, granite, quartzite and limestone GRAVEL (Shell fraction is sand to fine gravel sized, sand fraction is medium)	Yes	2.1	38.5	51.9	7.6	0.1	0.2		
1.25	Yellowish brown (10YR 5/6) slightly shelly slightly silty very gravelly medium to coarse SAND with occasional COBBLES (Shell fraction is sand to fine gravel sized, gravel fraction is fine to medium angular to rounded flint, sandstone, dolerite, and mudstone, cobble fraction is subrounded flint)	Yes	4.9	71.1	24.0		0.1	0.2		
1.56	Yellowish brown (10YR 5/6) medium to coarse SAND									
1.79	Yellowish brown (10YR 5/4) slightly silty very sandy fine to coarse angular to subrounded flint, quartzite and sandstone GRAVEL with occasional COBBLES (Sand fraction is medium to very coarse, cobble fraction is subangular flint)	Yes	1.2	26.5	64.2	8.1				
2.23	Light olive brown (2.5Y 5/4) slightly silty very sandy fine to coarse angular to subrounded flint and sandstone GRAVEL with occasional COBBLES (Sand fraction is medium, cobble fraction is subrounded flint)	Yes	4.8	39.2	46.7	9.4				
2.33	Light brownish grey (2.5Y 6/2) fine to coarse SAND									
3.01	Light brownish grey (2.5Y 6/2) slightly shelly slightly silty very sandy fine to medium angular to rounded flint, sandstone, quartzite, mudstone and quartz GRAVEL with occasional COBBLES (Shell fraction is sand to fine gravel sized, sand fraction is medium to very coarse, cobble fraction is subangular flint)	Yes	2.9	39.3	57.7			0.1		
3.36	Greyish brown (2.5Y 5/2) slightly shelly slightly gravelly fine to coarse SAND (Shell fraction is sand sized, gravel fraction is fine to medium subrounded to rounded flint, quartz and sandstone)									

End of Log at 3.36m

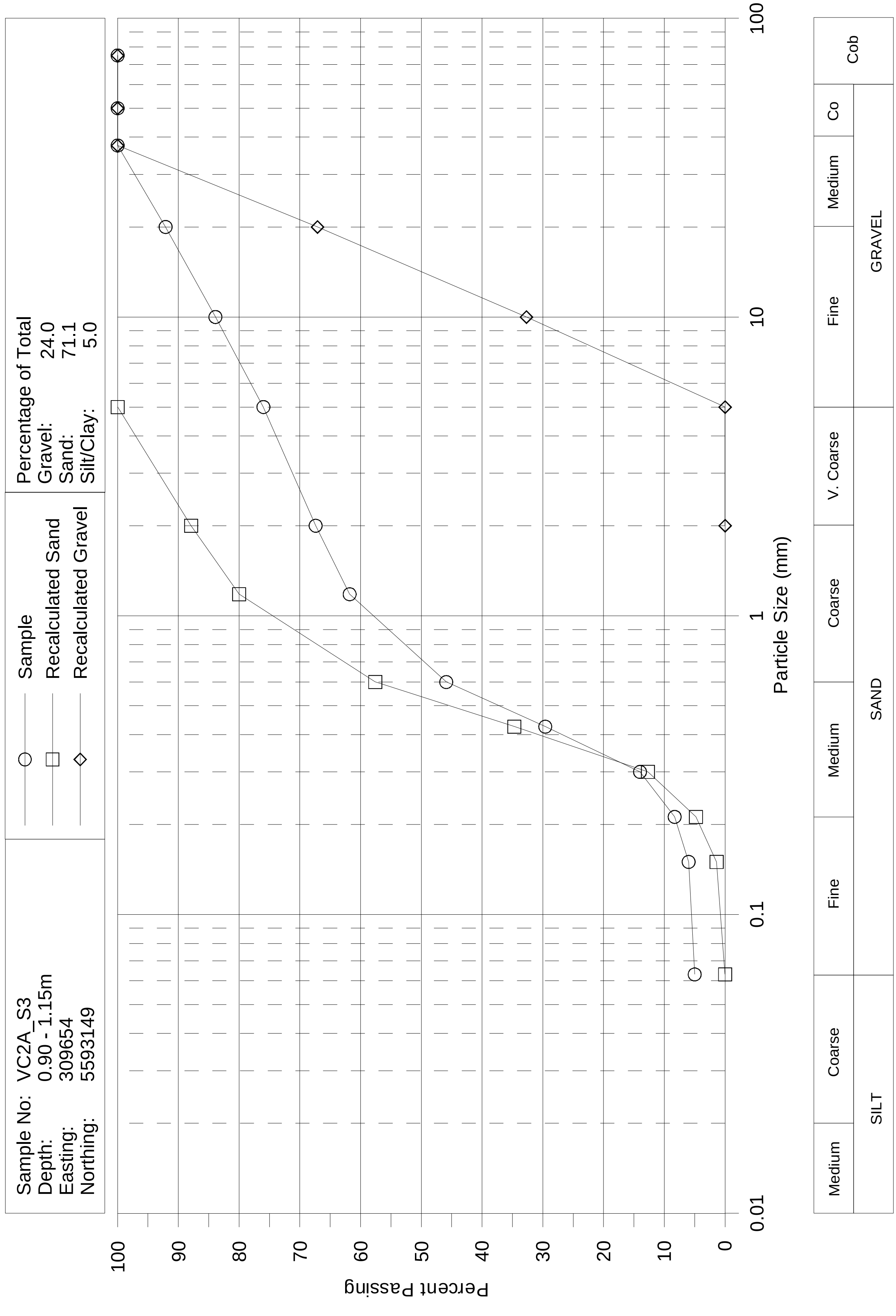
Depth scale: 1.0, 2.0, 3.0, 4.0, 5.0, 6.0

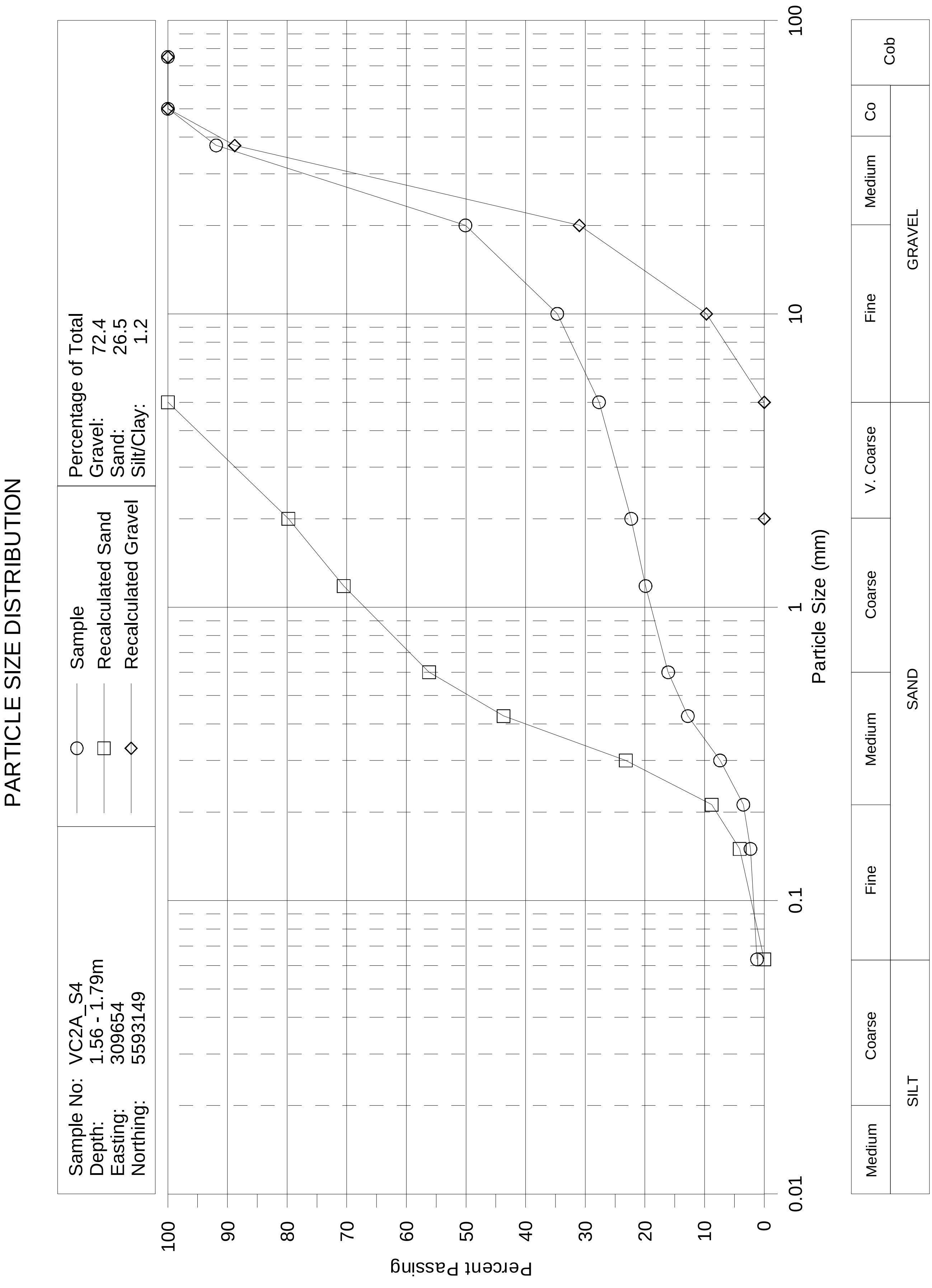
PENETRATION DEPTH (m): 4.58	**RECOVERY (m): 3.36**	**VESSEL: STRILBAS**

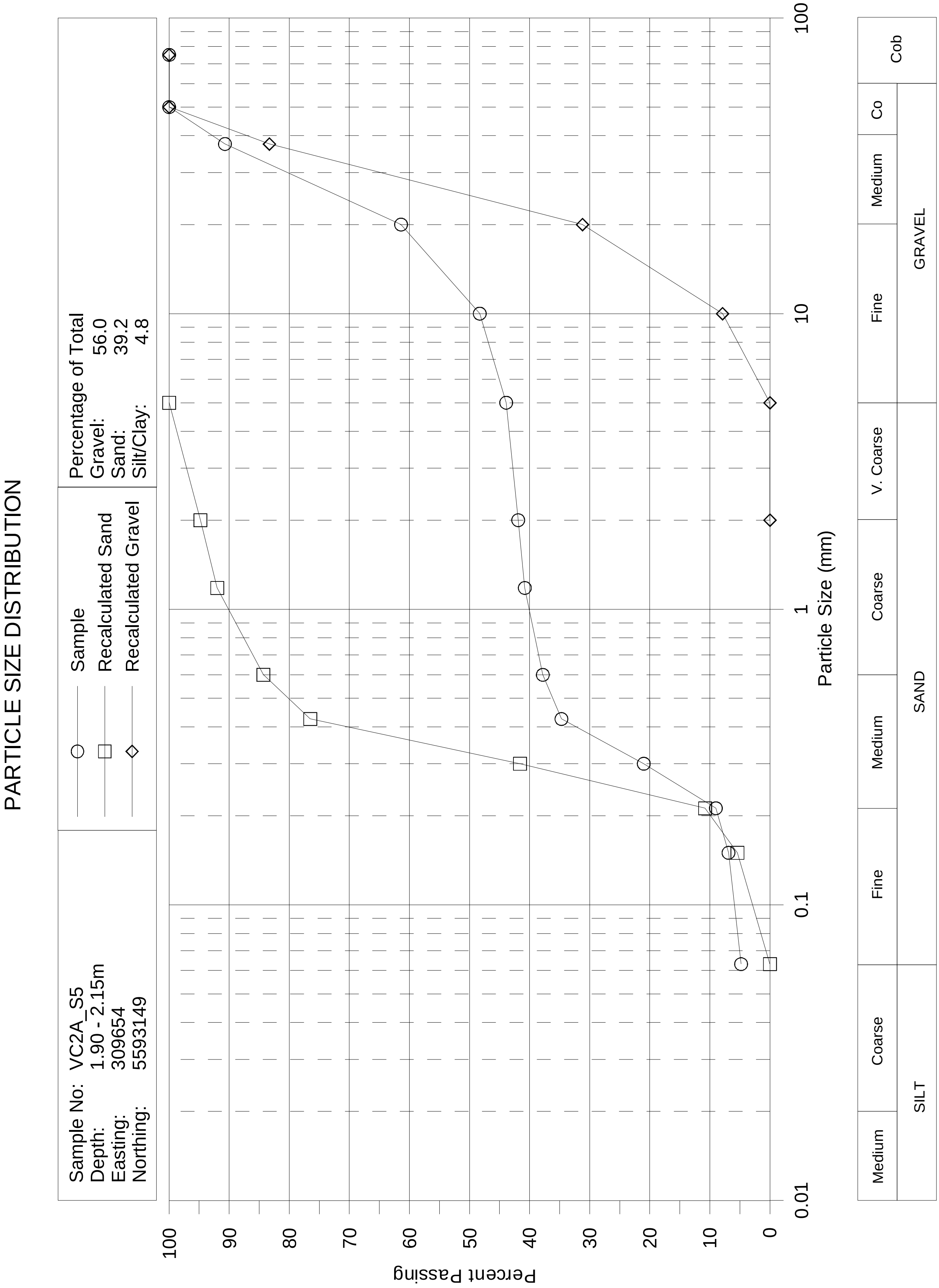

PARTICLE SIZE DISTRIBUTION
Sample No: VC2A_S1
Depth: 0.00 - 0.30m
Easting: 309654
Northing: 5593149
Sample
Recalculated Sand
Recalculated Gravel
Percentage of Total
Gravel: 42.2
Sand: 50.1
Silt/Clay: 7.8
Percent Passing
100
90
80
70
60
50
40
30
20
10
0
0.01
0.1
1
10
100
Particle Size (mm)
Medium
Coarse
Fine
Medium
Coarse
V. Coarse
Fine
Medium
Co
Cob
SILT
SAND
GRAVEL


PARTICLE SIZE DISTRIBUTION
Sample No: VC2A_S2
Depth: 0.50 - 0.70m
Easting: 309654
Northing: 5593149
Sample
Recalculated Sand
Recalculated Gravel
Percentage of Total
Gravel: 59.5
Sand: 38.5
Silt/Clay: 2.1
Percent Passing
100
90
80
70
60
50
40
30
20
10
0
0.01
0.1
1
10
100
Particle Size (mm)
Medium
Coarse
Fine
Medium
Coarse
V. Coarse
Fine
Medium
Co
Cob
SILT
SAND
GRAVEL

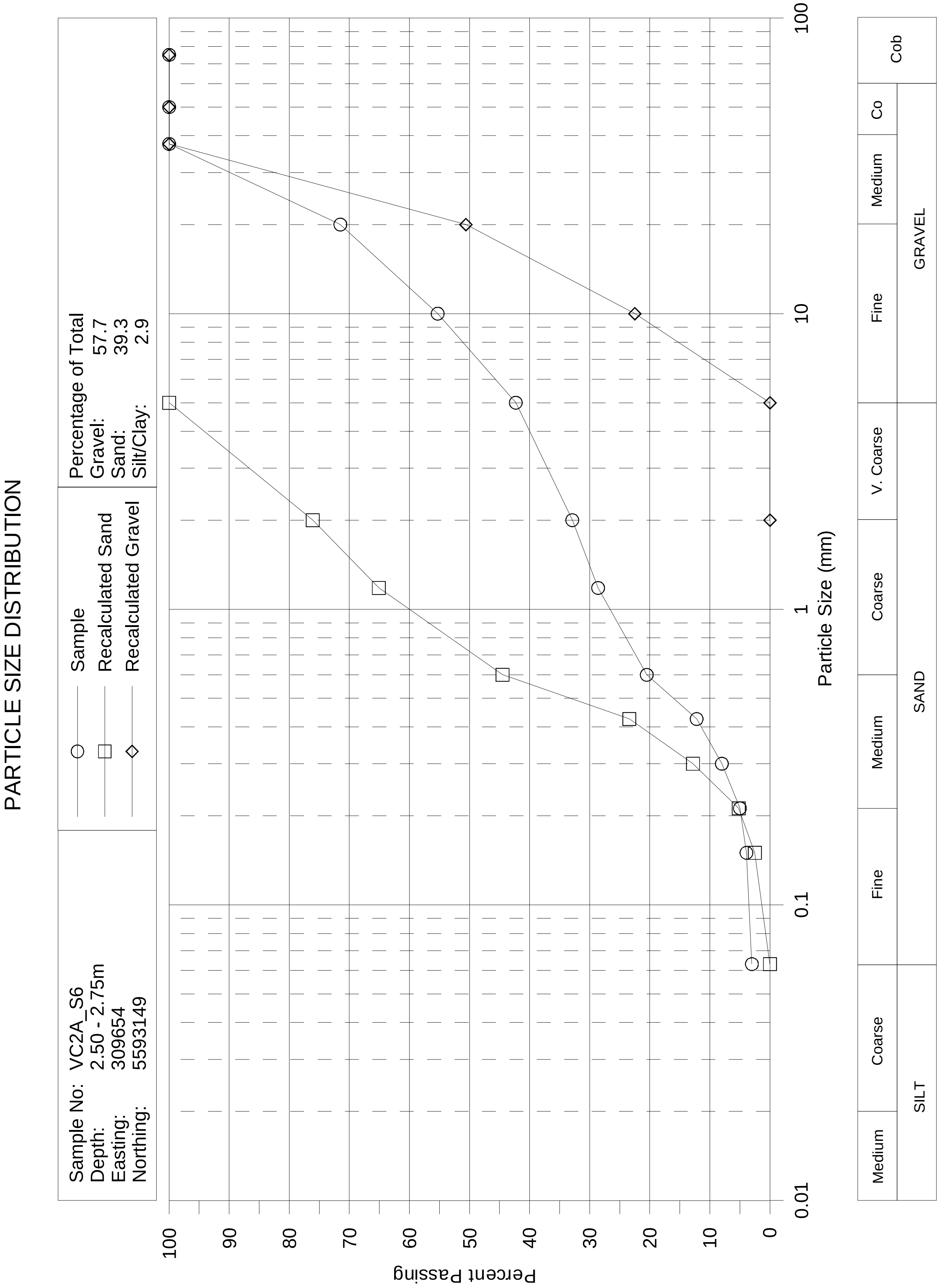
PARTICLE SIZE DISTRIBUTION




PARTICLE SIZE DISTRIBUTION
Sample No: VC2A_S4
Depth: 1.56 - 1.79m
Easting: 309654
Northing: 5593149
Sample
Recalculated Sand
Recalculated Gravel
Percentage of Total
Gravel: 72.4
Sand: 26.5
Silt/Clay: 1.2
Percent Passing
100
90
80
70
60
50
40
30
20
10
0
0.01
0.1
1
10
100
Particle Size (mm)
Medium
Coarse
Fine
Medium
Coarse
V. Coarse
Fine
Medium
Co
Cob
SILT
SAND
GRAVEL


PARTICLE SIZE DISTRIBUTION
Sample No: VC2A_S5
Depth: 1.90 - 2.15m
Easting: 309654
Northing: 5593149
Sample
Recalculated Sand
Recalculated Gravel
Percentage of Total
Gravel: 56.0
Sand: 39.2
Silt/Clay: 4.8
Percent Passing
100
90
80
70
60
50
40
30
20
10
0
0.01
0.1
1
10
100
Particle Size (mm)
Medium
Coarse
Fine
Medium
Coarse
V. Coarse
Fine
Medium
Co
Cob
SILT
SAND
GRAVEL

Hanson Aggregates Marine Limited
Area 473 West
Vibrocore Survey




VC 2A
0.00 - 3.36 M
5 SEPTEMBER 2003
AREA 473 WEST
HANSON
AGGREGATES
MARINE LIMITED
ANDREWS
SURVEY
PROJECT NO. 0609

Appendix C

Vibracore Acquisition Log

COASTLINE

Project No : 1245	Project Name: Vibrocoring	Corer: 5m HPC	Sheet : 1 of 1
Client : Hanson Marine	Vessel: MV Flatholm	Tolerance: 25m	Back up location :
Location : Newhaven	Personnel : AB, AC, JW	Rep: Claire Mellett	Coordinate System: WGS84 UTM N 31

CORE ID	ATTEMPT	DATE (dd/mm/yy)	TIME (hh:mm)	DESIGN LOCATION		CORED LOCATION		DISTANCE OFF TARGET (m)	WATER DEPTH (m)	FIX	PENETRATION (m)	RECOVERY (m)	VIBRATION TIME (min)	NO OF SECTIONS	REMARKS
				EASTING (m)	NORTHING (m)	EASTING (m)	NORTHING (m)								
HVC37b		16/03/2010	08:58	326547.35	5621079.53	326561.09	5621097.91	22.9	30	1	3.65	2.46	3	3	Course sand
HVC28		16/03/2010	09:54	327691.45	5622540.25	327683.29	5622555.86	17.6	25	2	3.77	1.76	3	2	Course sand. Poor recovery.
HVC28	Z	16/03/2010	10:24	327691.45	5622540.25	327686.85	5622552.3	12.9	25	3	0.00	-	-	-	Problem with vibrocorer. No recovery
HVC28	Y	17/03/2010	08:28	327691.45	5622540.25	327676.87	5622541.77	14.7	21	4	2.57	1.35	3	1	Sand
L3h		17/03/2010	09:11	329329.86	5621806.24	329352.11	5621804.58	22.3	23	5	5.00	1.52	4	1	Silty sand then cobbles
L3i		17/03/2010	09:43	329504.25	5621129.21	329529.96	5621126.68	25.8	32	6	4.60	2.70	3	3	Out of 25m zone. Client accepts. Silty sand with broken shell
HVC37a		17/03/2010	10:33	330251.24	5622671.78	330235.78	5622691.56	25.1	22	7	2.87	1.32	4	1	Out of 25m zone. Client accepts. Slightly silty sand with grav
L3b		17/03/2010	11:23	327787.54	5628065.08	327771.05	5628064.88	16.5	20	8	2.57	1.78	4	2	Gravel surrounded with sand
N4d		17/03/2010	14:42	295779.85	5610219.66	295786.32	5610218.25	6.6	55	9	2.19	1.23	4	1	Silty brown sand with gravel
N4c		17/03/2010	15:13	295756.91	5610212.5	295758.25	5610214.38	2.3	55	10	2.37	0.96	5	1	Slightly silty sand with gravel
N4b		17/03/2010	15:52	295640.44	5610175	295646.36	5610187.08	13.5	53	11	1.90	0.56	4	1	Grey sand with gravel clasts
N4b	Z	17/03/2010	16:18	295640.44	5610175	295644.93	5610193.25	18.8	53	12	1.68	0.23	5	1	Grey sand with gravel clasts
N4a		17/03/2010	16:51	295512.47	5610133.5	295509.79	5610124.35	9.5	53	13	1.53	0.25	4	1	Sand with gravel clasts
N4		17/03/2010	17:28	295449.25	5610114.5	295459.09	5610115.67	9.9	53	14	2.14	0.40	4	1	Sand with gravel clasts
L1a		17/03/2010	18:15	294801.54	5614171.18	294814.35	5614191.76	24.2	50	15	5.00	4.86	4	5	Silty sand with gravel clasts

Surveyor Name:..............................

Signature:..............................

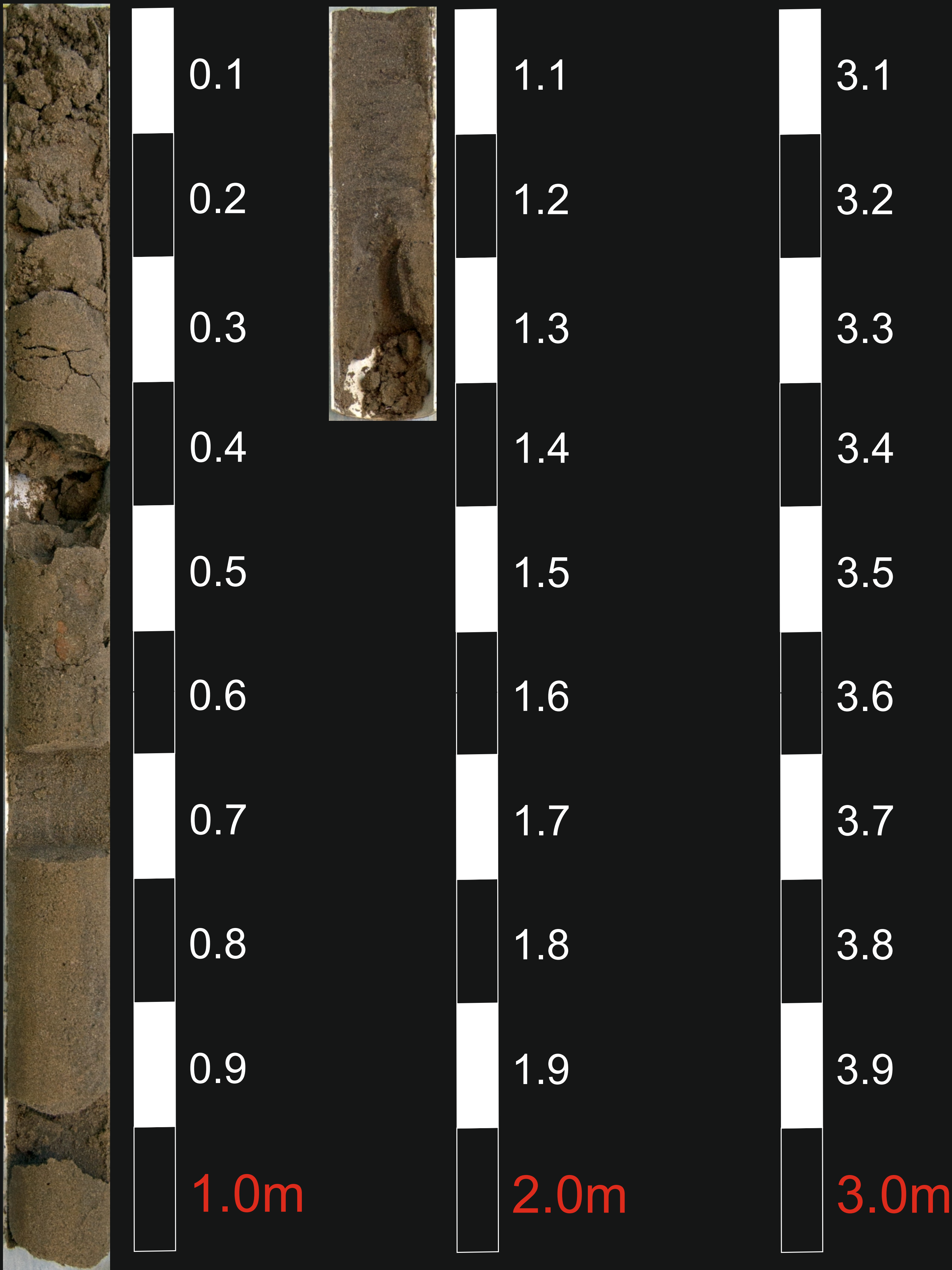
Appendix D

Completion Notes:	Site Number: *Hastings*	Date: *18.06.10*	Sheet: *1* of *1*
	Location: *VC28*		
		Logged By: *Claire Mellett*	
	Datum: *UTM Zone 31N*		
	Easting: *327676.87* mE		
	Northing: *5622541.77* mN		

UNIVERSITY OF LIVERPOOL

Grain Size: fS, mS, cS, vC, G — <187, 250, 375, 500, 750, 1000, 1500, 2000, Small pebbles, Med pebbles, Large pebbles, V L pebbles, Cobbles

Unit	Sample	Depth (m)	Lithology	Description	Interpretation
			0.00 - 0.23m	*Light Brown/beige well sorted slightly gravelly medium SAND. Gravel is granule size. High shell content, shell fragments granule size.*	
	OSL 1		*0.23 - 0.55m*	*Light brown/beige very poorly sorted gravelly medium SAND. Gravel is sub-angular to sub-rounded,small to very large pebble size. High shell content, shell fragments granule size.*	
	OSL 2	*0.5*	*0.55 - 1.35m*	*Light brown/beige well sorted slightly gravelly medium SAND. Gravel is sub-rounded, small pebble size. High shell content, shell fragments granule size.*	
	OSL 3	*1.0*			
			END OF CORE		
		1.5			
		2.0			
		2.5			
		3.0			
		3.5			



RGB

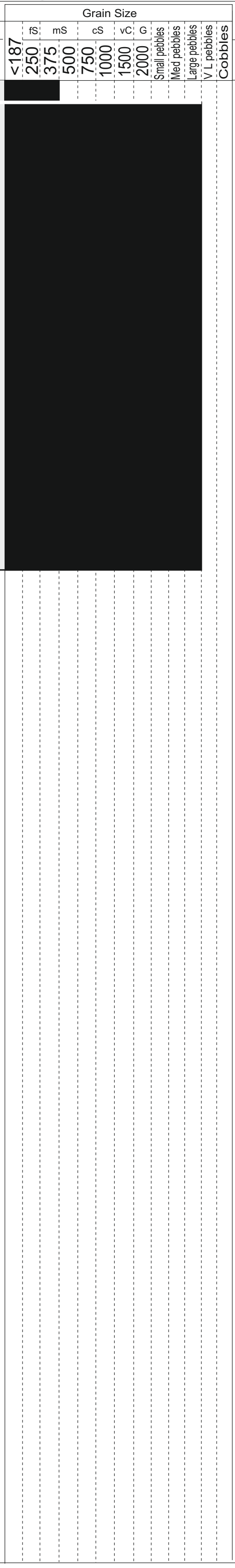
CMYK

Site Location: Hastings Bank
Core ID: VC28
Date: 18/06/2010

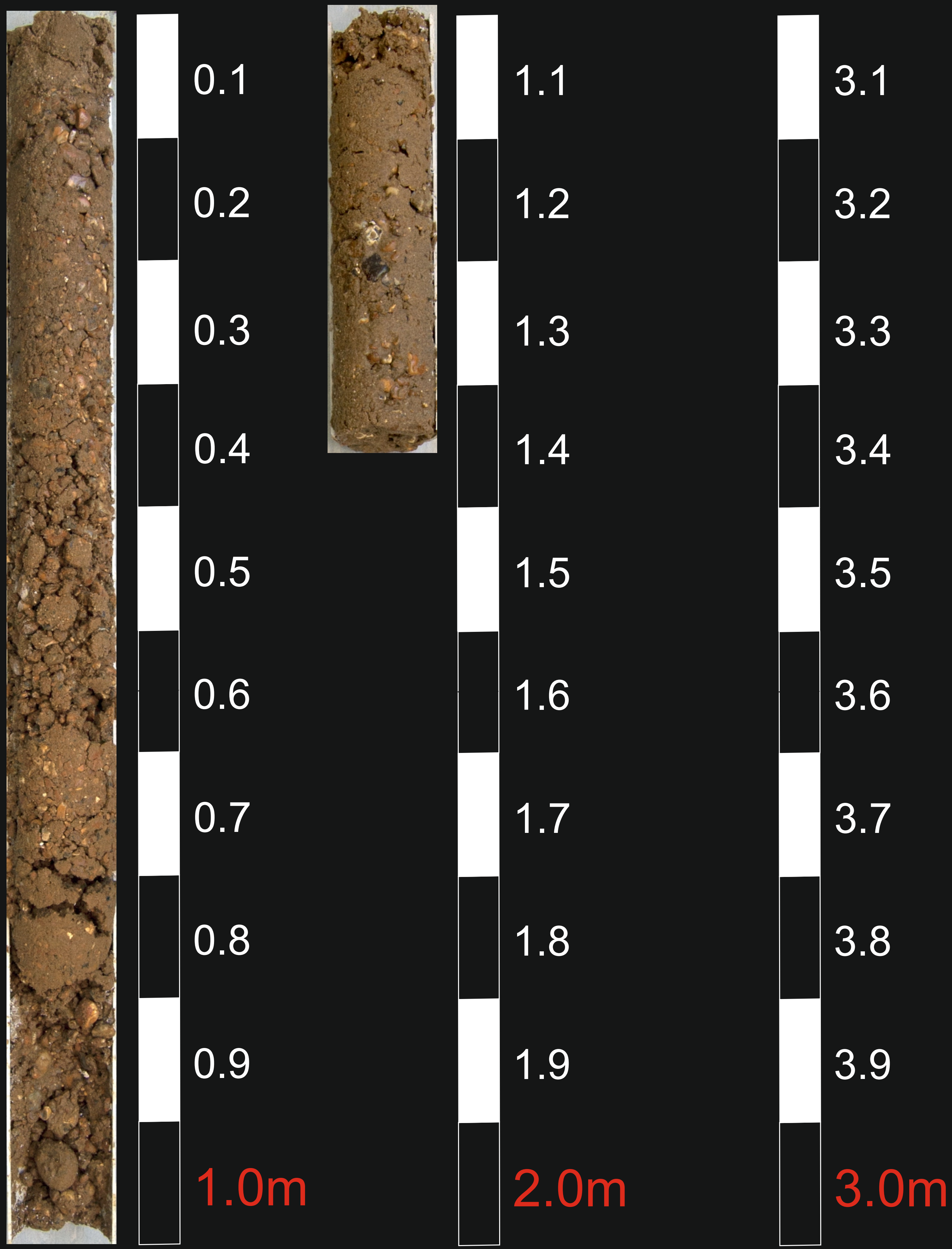
Completion Notes:	Site Number: *Hastings*	Date: *18.06.10*	Sheet: *1* of *1*
	Location: *VC37a*		
		Logged By: *Claire Mellett*	
	Datum: *UTM Zone 31N*		
	Easting: *330235.78* mE		
	Northing: *5622691.56* mN		

UNIVERSITY OF LIVERPOOL

Unit	Sample	Depth (m)	Lithology	Description	Interpretation
			0.00 - 0.06m	*Orange/brown moderately sorted slightly gravelly SAND. Gravel is granule size. High shell content, fragments only.*	
			0.06 - 1.32m	*Orange/brown clast supported very poorly sorted slightly sandy GRAVEL. Gravel is largely flint and quartz,sub-angular to sub-rounded, granule to very large pebble size. Larger clast are more rounded then smaller clasts. Shell fragments occur occasionally within the gravel.*	
			END OF CORE		



Depth (m): *0.5*, *1.0*, *1.5*, *2.0*, *2.5*, *3.0*, *3.5*



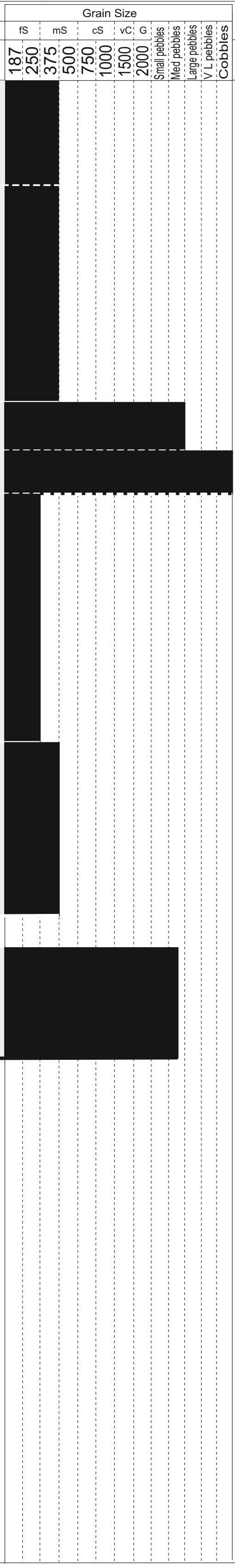
RGB

CMYK

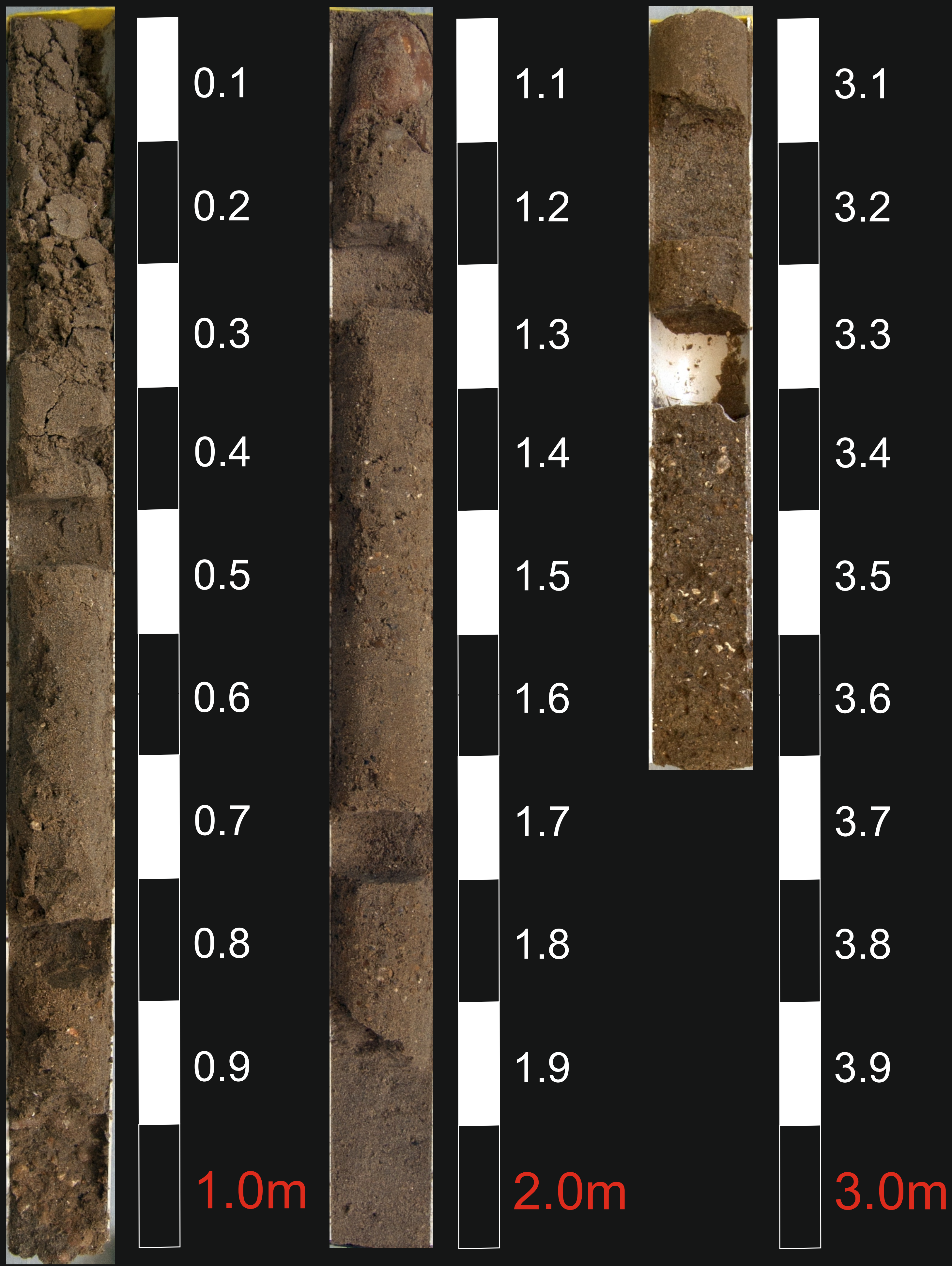
Site Location: Hastings Bank
Core ID: VC37a
Date: 18/06/2010

Completion Notes:	Site Number: *Hastings*	Date: *21.05.10*	Sheet: *1* of *1*
	Location: *VC37b*		
	Datum: *UTM Zone 31N*	Logged By: *Claire Mellett*	
	Easting: *326561.09* mE		
	Northing: *5621097.91* mN		

UNIVERSITY OF LIVERPOOL



Unit	Sample	Depth (m)	Lithology	Description	Interpretation
			0.00 - 0.29m	*Beige/brown moderately to well sorted SAND with high shell content and occasional fine gravel. Sediment disturbed when opening core.*	
	OSL 1, OSL 2	0.5	*0.29 - 0.88m*	*Beige/brown moderately to well sorted slightly gravelly SAND. Sand is medium and gravel is rounded, small to medium pebble size. High shell content both whole and fragmented*	
			0.88 - 1.00m	*Brown/orange matrix supported poorley sorted GRAVEL. Matrix is medium sand, gravel is sub-rounded to rounded, small to very large pebble size. Shell fragments present in matrix.*	
		1.0	*1.00 - 1.12m*	*Flint COBBLE rounded with low sphericity*	
	OSL 3, OSL 4	1.5	*1.12 - 1.79m*	*Beige/brown moderately to well sorted slightly gravelly fine SAND, Gravel is sub-rounded to rounded, small to medium pebble size. No apparent shell content. Gravel becomes more frequent with depth.*	
	OSL 5	2.0	*1.79 - 2.26m*	*Beige/brown slightly gravelly well sorted medium SAND. Gravel is granule size. Shell fragments of granule size present. Isolated silt pocket (2mm thick) present at base. Organic mottle at 2.25m*	
			2.26 - 2.34m	*VOID (pocket of air or water)*	
		2.5	*2.34 - 2.64m*	*Brown matrix supported very poorly sorted GRAVEL. Matrix is medium sand, gravel is largely flint, sub-angular to sub-rounded, granule to large pebble size.*	
			END OF CORE		
		3.0			
		3.5			



RGB

CMYK

Site Location: Hastings Bank
Core ID: VC37b
Date: 27/05/2010

Completion Notes:

Site Number: *0139* | Date: *16.09.10* | Sheet: *1* of *2*

Location: *VCL1a*

Logged By: *Claire Mellett*

Datum: *UTM Zone 31N*

Easting: *294814.35* mE

Northing: *5614191.76* mN

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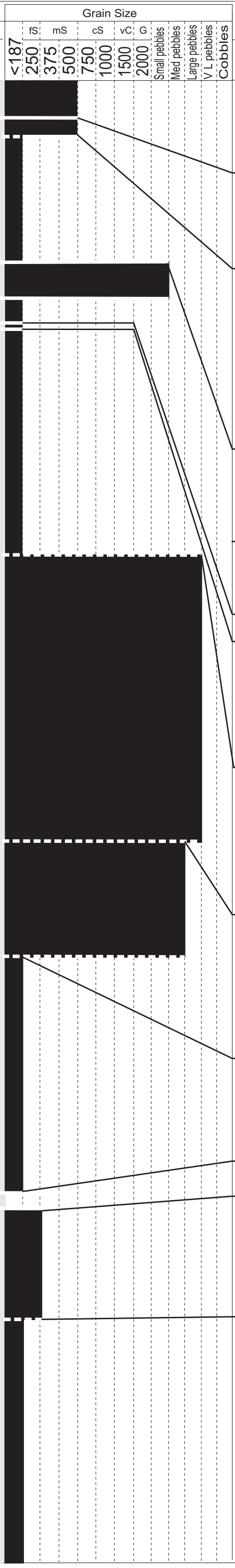
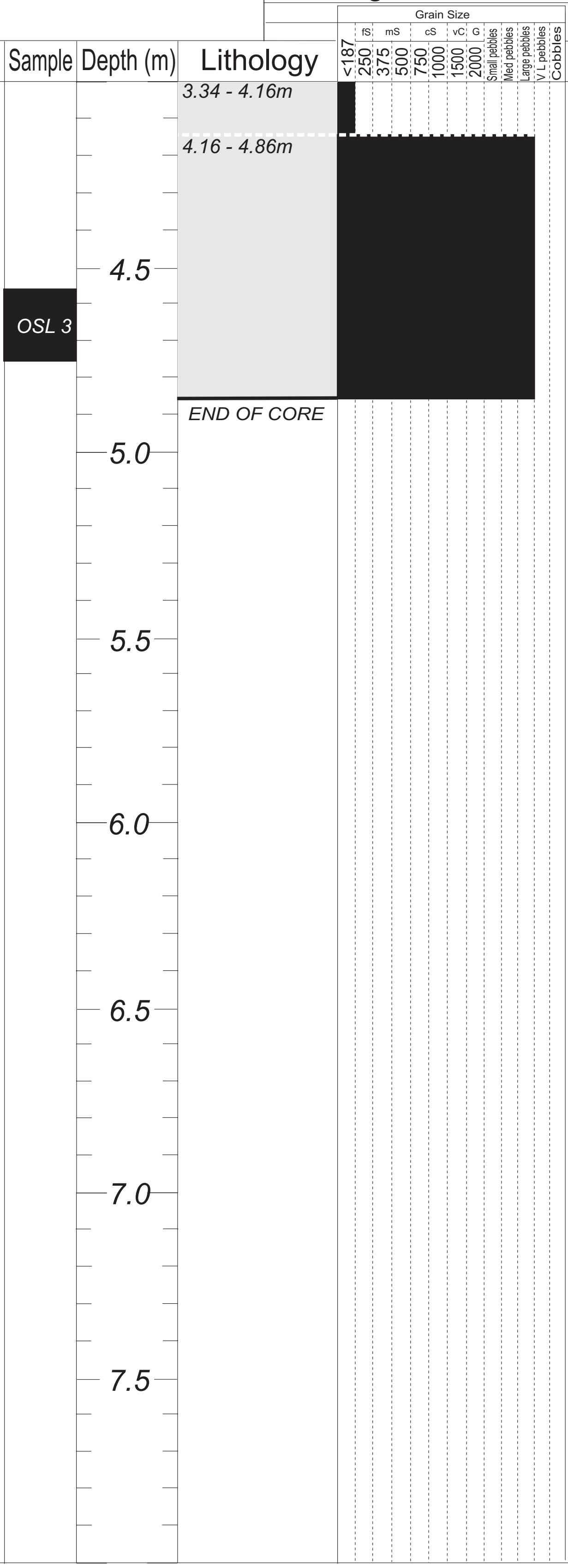
Unit	Sample	Depth (m)	Lithology	Description	Interpretation
			0.00 - 0.10m	*Orange/brown poorly sorted slightly gravelly very shelly medium SAND. Gravel is sub-angular, small to large pebble size, chert and flint. Shells are both fragmented and whole.*	
	OSL 1		*0.10 - 0.15m*	*Dark grey poorly sorted slightly silty slightly gravelly slightly shelly medium SAND. Gravel is sub-angular, small to large pebble size, chert and flint. Shell is fragmented.*	
		0.5	*0.15 - 0.49m*	*Grey moderately sorted slightly sandy gravelly SILT. Gravel is sub-angular, granule to small pebble size, chert and flint. Sand is fine. Organic mottles present becoming less frequent with depth. Fe mottle present throughout with 1cm mottle observed at 0.43cm. Sand and clay partings present throughout, 1cm thick clay band at 0.45cm. Possibly laminated.*	
			0.49 - 0.59m	*Grey poorly sorted slightly sandy silty matrix supported GRAVEL. Gravel is sub-angular, granule to large pebble size, chert and flint. Matrix is slightly sandy silt with Fe mottles.*	
			0.59 - 0.66m	*Grey moderately sorted slightly sandy slightly gravelly SILT. Gravel is sub-angular, granule to small pebble size, chert and flint. Sand is fine.*	
				Dark grey well sorted slightly silty CLAY.	
	OSL 2		*0.68 - 0.79m*	*Dark grey/brown poorly sorted slightly gravelly very sandy SILT. Gravel is sub-angular to angular, small pebble to medium pebble size, chert and occasional flint. Occasional Fe mottles. Sand is medium.*	
		1.0	*0.79 - 1.28m*	*Dark grey/brown very poorly sorted slightly sandy silty matrix supported GRAVEL. Gravel is angular to rounded (lithologically controlled), small to very large pebble size, chert and flint. Matrix is slightly sandy silt with sandier inclusions in places.*	
		1.5	*1.28 - 2.05m*	*Dark grey/brown very poorly sorted slightly sandy silty matrix supported GRAVEL. Gravel is angular to rounded (lithologically controlled), small to very large pebble size, chert and flint. Matrix is slightly sandy silt. Pockets of clay and sand present in matrix.*	
		2.0	*2.05 - 2.36m*	*Dark grey/brown very poorly sorted slightly sandy gravelly SILT. Gravel is angular to rounded , small to very large pebble size, chert and flint. Frequent pockets of clay.*	
	OSL 5	*2.5*	*2.36 - 3.00m*	*No sample, post coring compaction*	
		3.0	*3.04 - 3.34m*	*Brown very poorly sorted slightly gravelly silty fine to medium SAND. Gravel is sub-rounded to sub-angular, small pebble to medium pebble size, chert and occasional flint. Pockets of silty sand and silt clay frequent throughout.*	
	OSL 4	*3.5*	*3.34 - 4.16m*	*Brown/grey moderately sorted slightly gravelly very sandy SILT. Gravel is sub-angular to sub-rounded, small pebble to medium pebble size, chert. Frequent organic and Fe mottles and occasional clay partings. 3.60m - 4.00m evidence of dewatering. (continues on separate sheet)*	

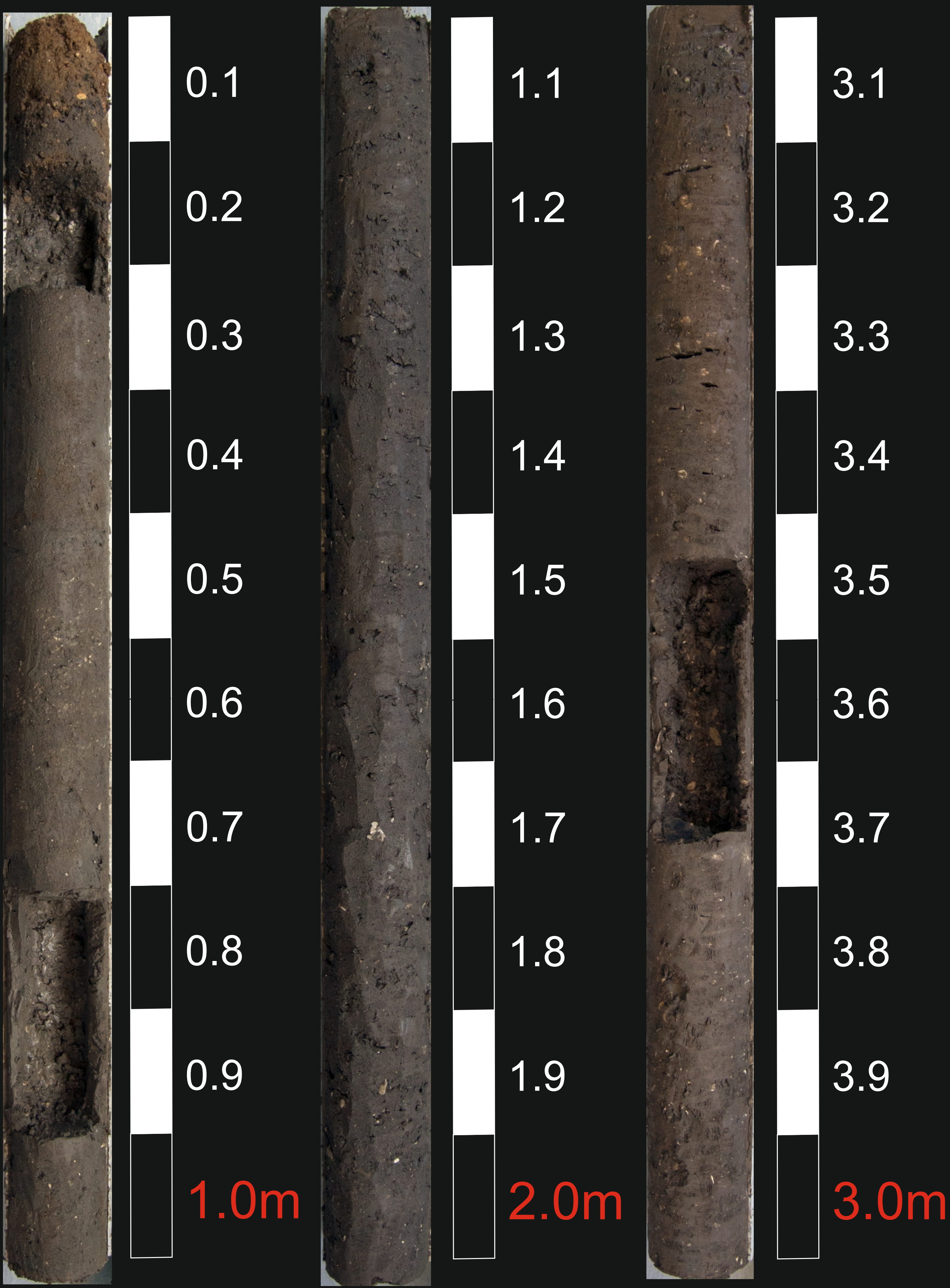


CONTINUED ON SEPARATE SHEET

Completion Notes:	Site Number: *0139*	Date: *16.09.10*	Sheet: *2* of *2*
	Location: *VCL1a*		
		Logged By: *Claire Mellett*	
	Datum: *UTM Zone 31N*	UNIVERSITY OF LIVERPOOL	
	Easting: *294814.35* mE		
	Northing: *5614191.76* mN		

Unit	Sample	Depth (m)	Lithology	Description	Interpretation
			3.34 - 4.16m	*See previous sheet.*	
	OSL 3	*4.5*	*4.16 - 4.86m*	*Brown very poorly sorted silty matrix supported GRAVEL. Gravel is sub-angular, small pebble to very large pebble size, chert and occasional flint. Matrix is silt.*	
			END OF CORE		





RGB

CMYK

Site Location: 0139
Core ID: VCL1a
Date: 27/05/2010

Sheet 1 of 2

RGB

CMYK

Site Location: 0139
Core ID: VCL1a
Date: 27/05/2010

Completion Notes:	Site Number: *Hastings*	Date: *27.05.10*	Sheet: *1* of *1*
	Location: *VCL3b*		
	Datum: *UTM Zone 31N*	Logged By: *Claire Mellett*	
	Easting: *327771.05* mE		
	Northing: *5628064.88* mN		

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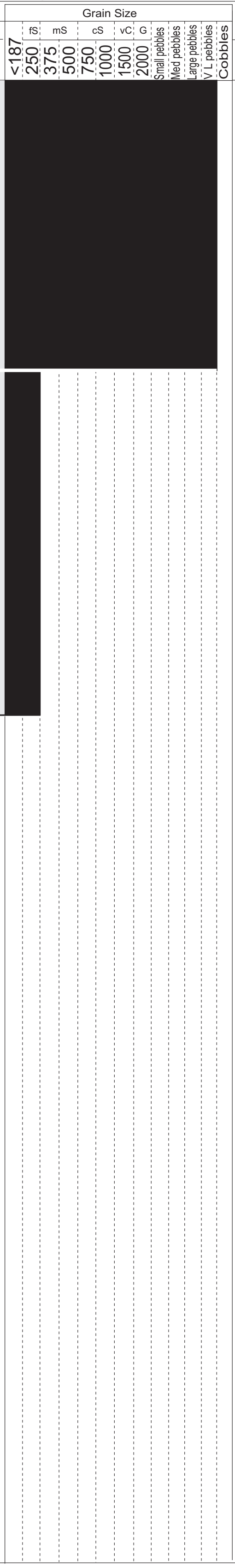
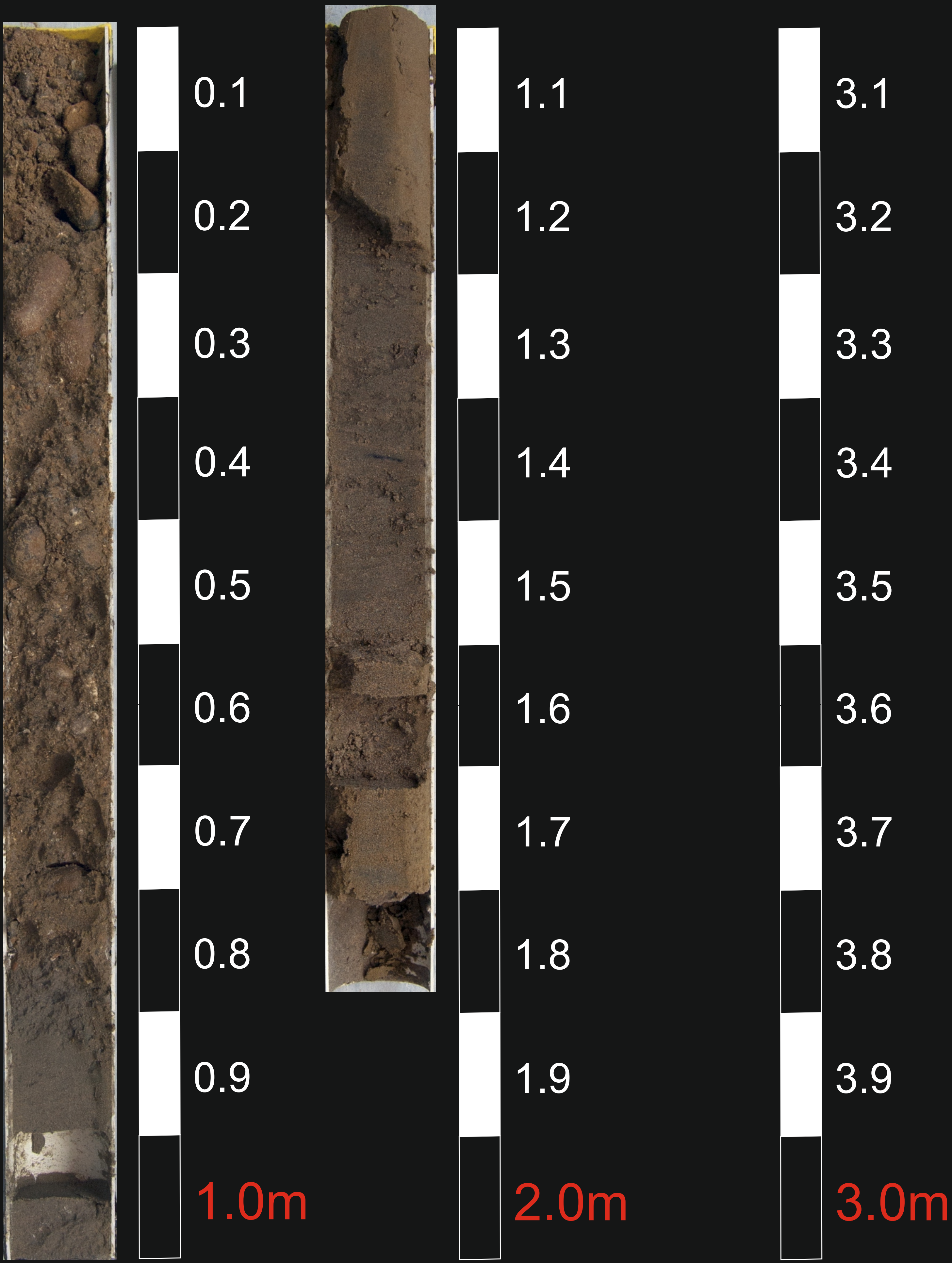
Unit	Sample	Depth (m)	Lithology	Description	Interpretation
	OSL 1		*0.00 - 0.79m*	*Orange/brown matrix supported very poorly sorted sandy GRAVEL. Matrix is coarse sand, gravel is of various lithologies, rounded to sub-rounded, low sphericity, small pebble to large pebble size.*	
	OSL 3	1.0	*0.79 - 1.71m*	*Grey/brown very well sorted slightly silty fine sand with occasional shell fragments. Possibly finely laminated. Clay laminae present at 1.37m.*	
	OSL 2	1.5			
			END OF CORE		

Depth scale (m): 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5





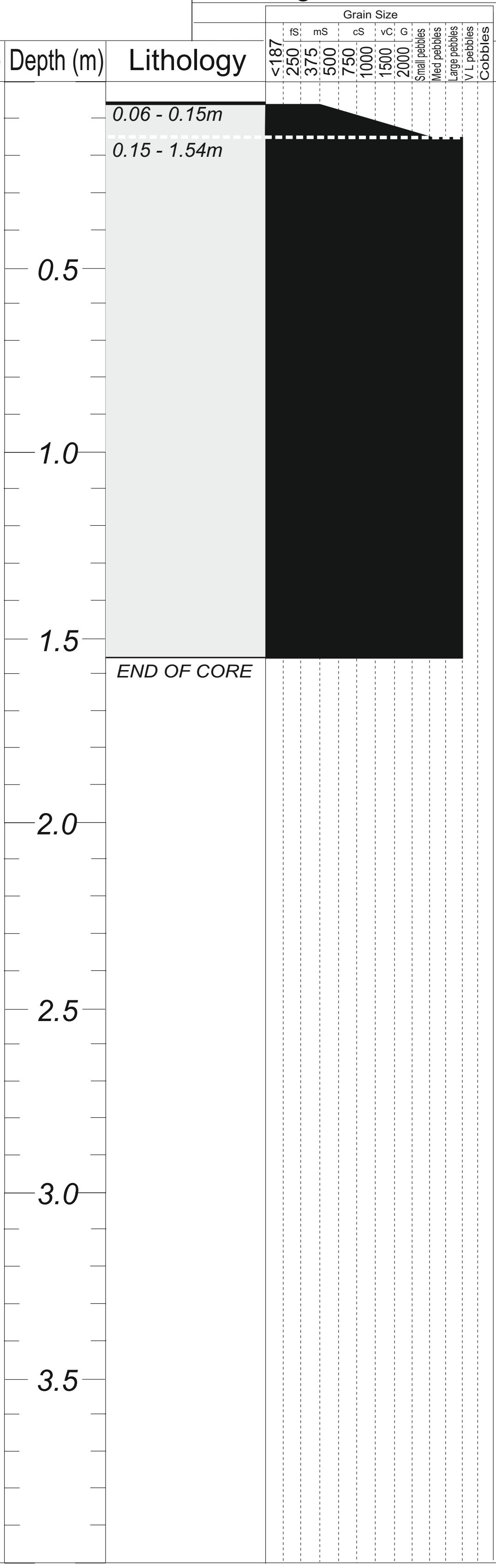
RGB

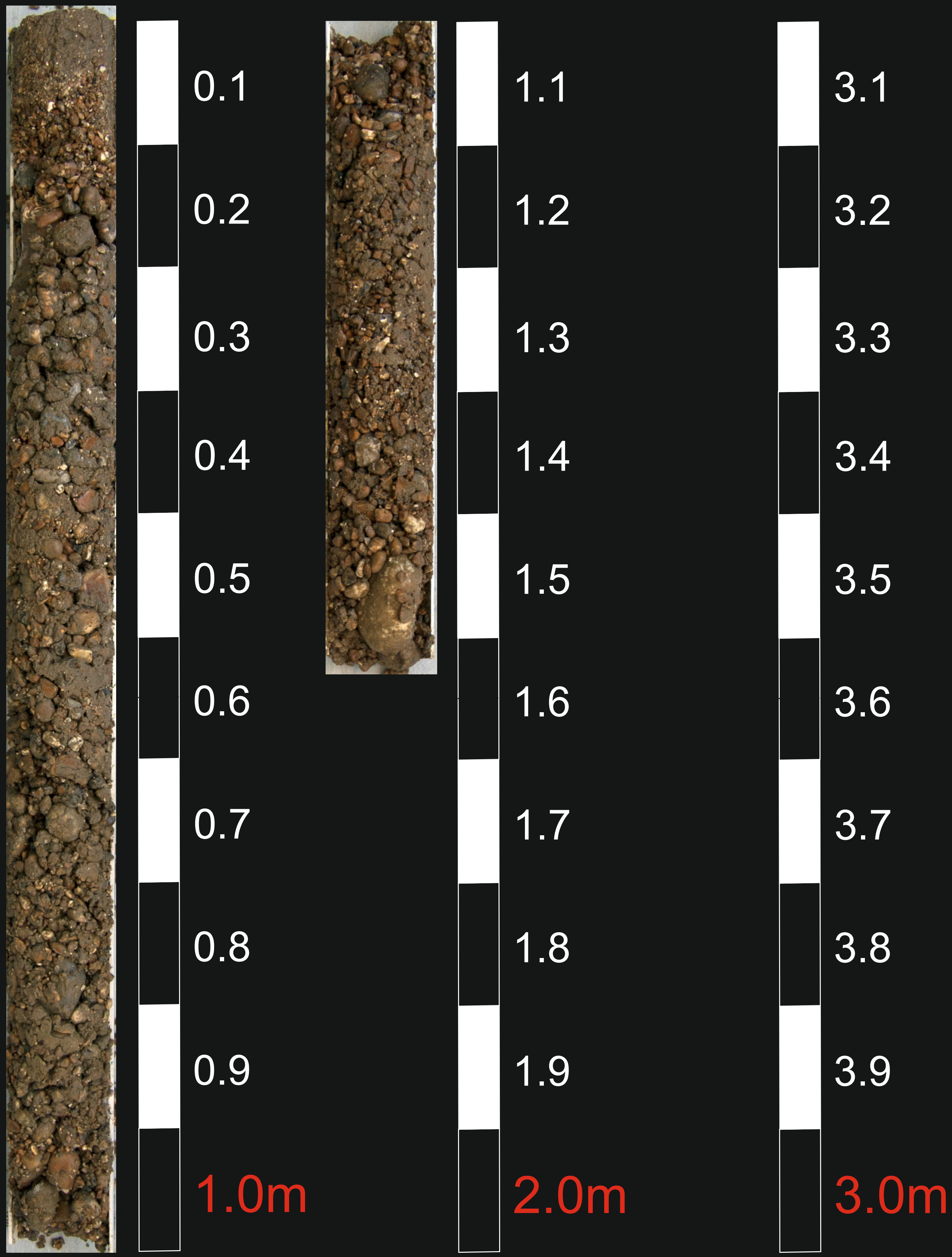
CMYK

Site Location: Hastings Bank
Core ID: VCL3b
Date: 27/05/2010

Completion Notes:	Site Number: *Hastings*	Date: *18.06.10*	Sheet: *1* of *1*
	Location: *VCL3h*		
	Datum: *UTM Zone 31N*	Logged By: *Claire Mellett*	
	Easting: *329352.11* mE	UNIVERSITY OF LIVERPOOL	
	Northing: *5621804.58* mN		

Unit	Sample	Depth (m)	Lithology	Grain Size	Description	Interpretation
			0.06 - 0.15m		*No sample*	
					Brown moderately sorted slightly gravelly medium SAND. Gradually coarsens with depth into poorly sorted fine gravel. High shell content, both whole and fragmented.	
			0.15 - 1.54m		*Brown very poorly sorted slightly sandy clast supported GRAVEL. Gravel is largely flint and quartz sub-angular to sub-rounded, high sphericity, small to very large pebble size. A cobble ca.10cm in size is present at 0.20m. High shell content becoming less frequent with depth. A cobble blocks the end of the core.*	
			END OF CORE			





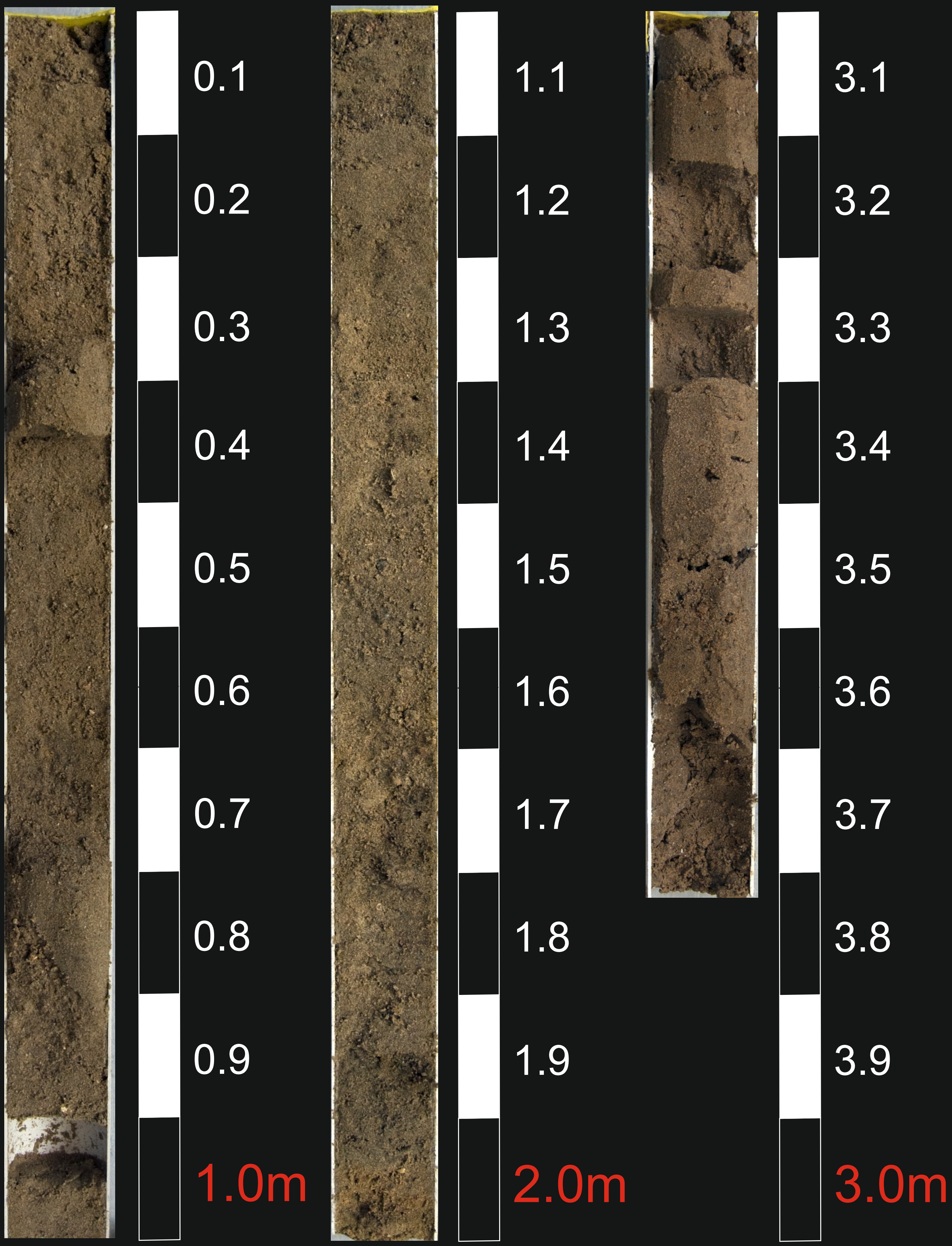
RGB
CMYK

Site Location: Hastings Bank
Core ID: VCL3h
Date: 18/06/2010

Completion Notes:	Site Number: *Hastings*	Date: *27.05.10*	Sheet: *1* of *1*
	Location: *VCL3i*		
	Datum: *UTM Zone 31N*	Logged By: *Claire Mellett*	
	Easting: *329529.96* mE		
	Northing: *5621126.68* mN		

Grain Size: <187 | fS 250 | mS 375, 500 | cS 750, 1000 | vC 1500 | G 2000 | Small pebbles | Med pebbles | Large pebbles | V L pebbles | Cobbles

Unit	Sample	Depth (m)	Lithology	Description	Interpretation
	OSL 4, OSL 5, OSL 1, OSL 3, OSL 2, OSL 6	0.5, 1.0, 1.5, 2.0, 2.5	*0.00 - 2.70m*	*Brown/orange moderately to well sorted medium slightly gravelly SAND. High shell content both whole and fragmented. Gravel is sub-angular to sub-rounded medium pebble size. Colour change to grey/beige after 1.75m. Organic mottle at 1.17m.*	
		3.0, 3.5	END OF CORE		

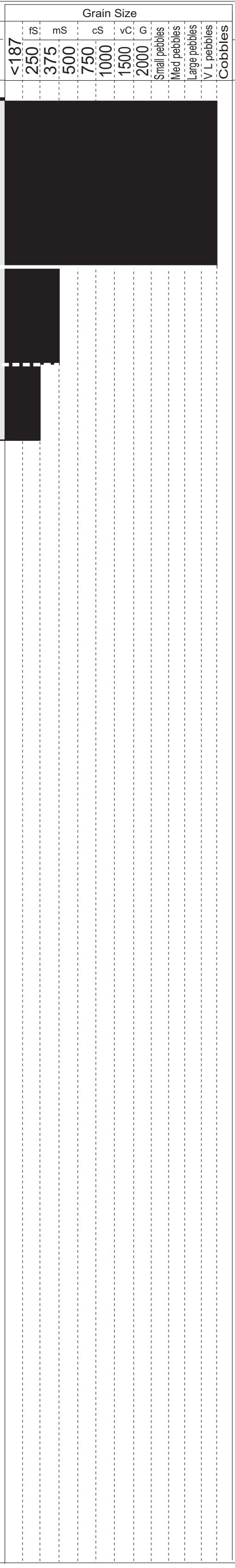


RGB

CMYK

Site Location: Hastings Bank
Core ID: VCL3i
Date: 27/05/2010

Completion Notes:	Site Number: *0139*	Date: *28.05.10*	Sheet: *1* of *1*
	Location: *VCN4c*		
		Logged By: *Claire Mellett*	
	Datum: *UTM Zone 31N*	UNIVERSITY OF LIVERPOOL	
	Easting: *295758.25* mE		
	Northing: *5610214.38* mN		



Unit	Sample	Depth (m)	Lithology	Description	Interpretation
				No sample	
	OSL 1		*0.06 - 0.50m*	*Brown matrix supported very poorly sorted slightly clayey, sandy GRAVEL. Matrix is coarse sand, gravel is sub-rounded, granule to cobble size. Shell fragments and pockets of clay present in matrix.*	
		0.5	*0.50 - 0.77m*	*Brown moderately sorted slightly gravelly medium SAND. Gravel is chert, sub-angular, medium pebble size.*	
	OSL 2		*0.77 - 0.97m*	*Brown well sorted silty fine SAND. Possibly finely laminated. Organic mottle present at 0.88m.*	
		1.0	END OF CORE		
		1.5			
		2.0			
		2.5			
		3.0			
		3.5			

0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0m

1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0m

3.1
3.2
3.3
3.4
3.5
3.6
3.7
3.8
3.9
3.0m

RGB
CMYK

Site Location: 0139
Core ID: VCN4c
Date: 17/05/2010

Completion Notes:	Site Number: *0139*	Date: *18.06.10*	Sheet: *1*	of *2*
	Location: *VCN4d*			
		Logged By: *Claire Mellett*		
	Datum: *UTM Zone 31N*			
	Easting: *295786.32* mE			
	Northing: *5610218.25* mN			

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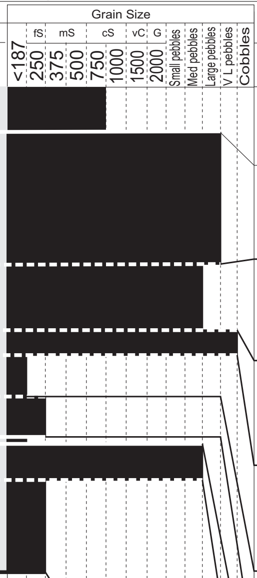
Unit	Sample	Depth (m)	Lithology	Description	Interpretation
			0.00 - 0.12m	*Orange/brown poorly sorted slightly gravelly coarse SAND. Gravel is sub-rounded , granule to small pebble size. Frequent shell fragments.*	
	OSL 3		*0.12 - 0.44m*	*Brown/orange matrix supported very poorly sorted GRAVEL. Matrix is slightly silty fine sand, gravel is largely flint, sub-rounded, small pebble to cobble size.*	
		0.5	*0.44 - 0.61m*	*Brown matrix supported very poorly sorted GRAVEL. Matrix is fine to medium sand, gravel is largely chert, Sub-angular, small to large pebble size*	
			0.61 - 0.67m	*Light brown matrix supported very poorly sorted GRAVEL. Matrix is slightly silty fine sand, gravel is largely flint with small chert clasts. Gravel is sub-angular, small to very large pebble size.*	
	OSL 1		*0.67 - 0.77m*	*Brown/light brown moderately to well sorted slightly gravelly silty fine SAND. Possibly finely laminated. Gravel is sub-rounded, small pebble size.*	
			0.77 - 0.87m	*Brown/light brown poorly sorted gravelly fine SAND. Gravel is largely sub-angular flint and sub-rounded chert, small to large pebble size.*	
				Brown moderately sorted very silty fine SAND. Possible finely laminated.	
			0.89 - 0.98m	*Light brown matrix supported very poorly sorted GRAVEL. Matrix is fine sand, gravel is largely sub-angular flint and sub-rounded chert, small to large pebble size.*	
	OSL 2	*1.0*	*0.98 - 1.21m*	*Light brown moderately to well sorted slightly gravelly fine sand. Gravel is sub-rounded, small pebble size.*	
			END OF CORE		
		1.5			
		2.0			
		2.5			
		3.0			
		3.5			



0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0m

1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0m

3.1
3.2
3.3
3.4
3.5
3.6
3.7
3.8
3.9
3.0m

RGB
CMYK

Site Location: 0139
Core ID: VCN4d
Date: 18/06/2010